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A KNOWLEDGE-BASE FOR REHABILITATION OF AIRFIELD CONCRETE PAVEMENTS

BY

WAYNE JOSEPH SEILER

B.S., United States Air Force Academy, 1979
M.S., University of Illinois, 1985

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Civil Engineering
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A KNOWLEDGE-BASE FOR REHABILITATION OF AIRFIELD CONCRETE PAVEMENTS

Wayne Joseph Seiler, Ph.D.
Department of Civil Engineering
University of Illinois at Urbana-Champaign, 1991
M. Darter, Advisor

Airfield pavement knowledge captured in this research showed that knowledge-based techniques can be used to quickly select and design rehabilitation alternatives for a runway, taxiway or an apron. The AIRfield PAvement Consultant System (AIRPACS) uses the knowledge of planners, constructors, airfield managers and designers to solve difficult jointed plain concrete pavement (JPCP) design problems. This expert system focuses on aircraft safety and pavement structural capacity which are key issues for all pavement design participants. During the validation tests, AIRPACS recommendations were compared to results that were obtained using current empirical and mechanistic design procedures. The results demonstrate that the knowledge acquired and represented in AIRPACS will allow knowledgeable pavement engineers to quickly perform airport rehabilitation designs.

AIRPACS uses the knowledge of pavement design participants and specific airfield information to perform rehabilitation designs. An expert's knowledge is represented using heuristics, or "rules of thumb", while airfield information is represented using collections of objects. Airfield objects have been grouped into classes such as aircraft, JPCP components, JPCP distresses, climate regions and JPCP repairs. All objects within these classes contain information which describes inherent attributes of the object as well as interrelationships among objects within the airport environment. This natural representation of the airport environment makes it easy to understand the rules in AIRPACS which represent an expert's problem solving knowledge.

AIRPACS uses design expertise to select feasible rehabilitation alternatives for a specific area, or feature, of a runway, taxiway or apron. Routine maintenance, restoration, safety enhancing overlays and structural improvements are considered in the initial feasibility study. If a structural improvement is required, AIRPACS reviews pavement evaluation data and the airport environment to decide if reconstruction, or one of several overlay types, is feasible. Mechanistic, heuristic and empirical design methods are then used to select a new

JPCP thickness, JPCP or asphalt concrete overlay thickness, joint types and joint spacings.

The reliability of AIRPACS recommendations were compared to recommendations made by a pavement consultant firm for several projects. Consultant reports used in the validation process included airfields located in several climatic regions of the United States. These reports use a mechanistic design approach but always compare the results to Air Force Manual 88-6 or the Federal Aviation Administration design procedures. Although all expert systems must be continually updated and enhanced, this research demonstrated that the knowledge captured in AIRPACS can be used to provide reasonable design solutions for JPCP rehabilitation in the airport environment.

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I want to thank Professor Michael I. Darter for the advice, support and encouragement that he provided during the course of this research. His expertise and guidance were invaluable and helped me focus on key goals throughout this research. However, the timely completion of this research also depended on the additional guidance provided by Professor James H. Garrett. His dedication, enthusiasm, and expertise in the area of knowledge-based expert systems helped to make this research effort a success. Sincere appreciation must also be expressed to Professors Barry J. Dempsey and Anastasios M. Ioannides for their moral and technical support. The ideas and concepts they shared with me helped me overcome obstacles that were encountered during this research.

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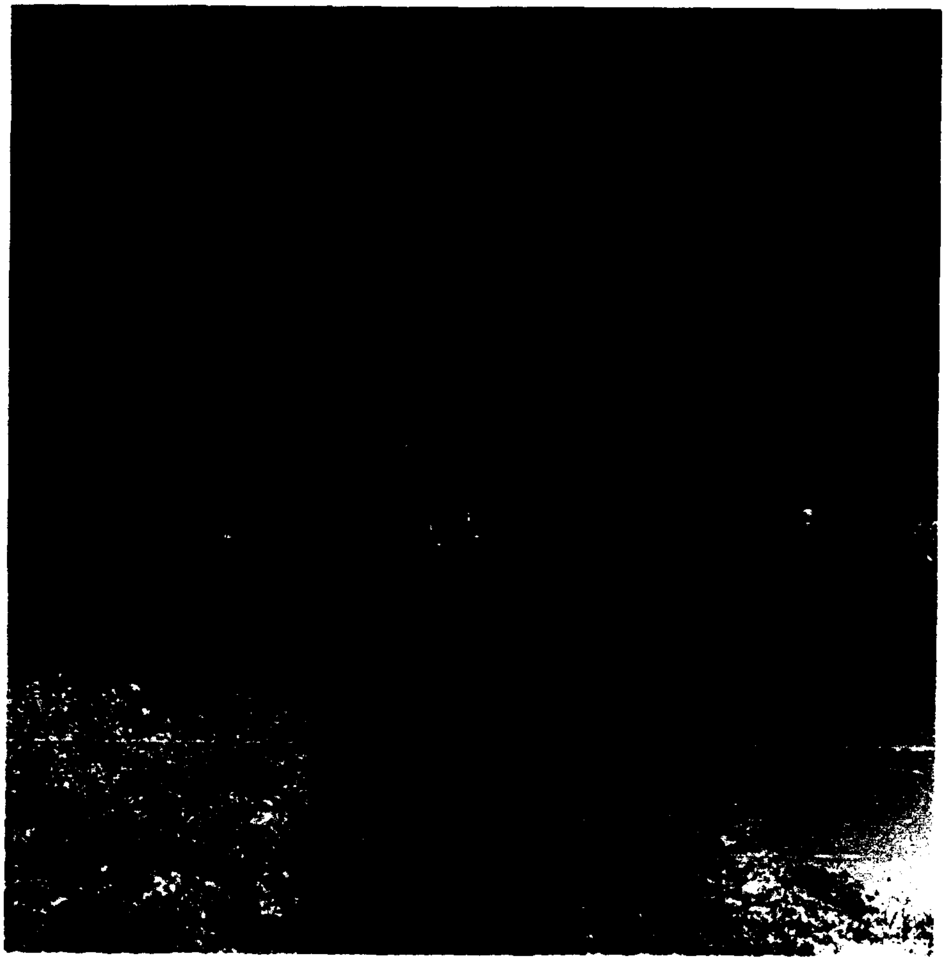
Finally, I wish to thank my wife, Jill, for her support and understanding during our three years at the University of Illinois. This research consumed many hours that would have otherwise been spent with the family. However, I hope that Jill and our children, Robert, Christopher, and Sabrina, will see the emphasis that I give education and use this as a personal motivator throughout their careers.

"MAN'S FLIGHT THROUGH LIFE IS SUSTAINED BY THE POWER OF HIS KNOWLEDGE"

Austin "Dusty" Miller



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LIST OF ABBREVIATIONS

a	=	load radius, inches
AC	=	asphalt concrete
AC	=	Advisory Circular
AFM	=	Air Force Manual
AT	=	air temperature, degrees Kelvin
AIRPACS	=	AIRfield PAvement Consultant System
APSD	=	airfield pavement system description
BCE	=	Base Civil Engineering
C_b	=	condition factor for AC overlay design
COE	=	Corps of Engineers
COV	=	coverages
C_r	=	condition factor for PCC overlay design
CRCP	=	continuously reinforced concrete pavement
C_{xc}	=	maximum ordinate of aircraft placement distribution
DLTE	=	deflection load transfer efficiency
DMT	=	decision-making tools
DOD	=	Department of Defense
DPDM	=	design process decision maker
DTS	=	decision tree summary
E	=	elastic modulus, psi
E_c	=	PCC elastic modulus, psi
ESAL	=	equivalent single-axle load
ESAR	=	equivalent single-axle radius
ESWL	=	equivalent single wheel load
ESWR	=	equivalent single wheel radius
E_o	=	existing PCC elastic modulus, psi
EUAC	=	equivalent uniform annual cost
F	=	base slab cracking factor for AC overlay design
FAA	=	Federal Aviation Administration
FCI	=	FOD Condition Index
FOD	=	foreign object damage
FSL	=	Fatigued Single Layer
FWD	=	Falling Weight Deflectometer
f(z)	=	probability density function of standardized normal variable
GI	=	group index
in	=	inches
k	=	modulus of subgrade reaction, psi/inch
K	=	modulus of dowel support, psi
KB	=	knowledge-base
KBES	=	knowledge-based expert system
KBS	=	knowledge-based system
KS	=	knowledge sources
h	=	pavement layer thickness, inches
i	=	discount rate, percent
JPC	=	jointed plain concrete
JPCP	=	jointed plain concrete pavement
JRCP	=	jointed reinforced concrete pavement
L	=	slab length, feet
ℓ	=	radius of relative stiffness, inches
lbs	=	pounds

LIST OF ABBREVIATIONS

μ	=	population mean
μ	=	Poisson's ratio
PFC	=	porous friction course
MR	=	modulus of rupture of PCC, psi
M&R	=	maintenance and repair
MAJCOM	=	Major Command
n	=	number of years considered in cost analysis
n	=	number of actual aircraft passes
N	=	number of allowable aircraft passes
NSL	=	New Single Layer
O&M	=	operations and maintenance
P/C	=	pass-to-coverage ratio
PCI	=	Pavement Condition Index
PCC	=	Portland cement concrete
psi	=	pounds per square inch
PW	=	present worth
ROD	=	rate of deterioration
SCI	=	Structural Condition Index
SLTE	=	stress load transfer efficiency
SF	=	shift factor, degrees Kelvin
S_x	=	standard deviation of aircraft placement distribution
UER	=	unscheduled engine removal
W	=	slab width, feet
W_t	=	tire width, inches
z	=	standard normal deviate

CHAPTER 1

INTRODUCTION

Those who attend the United States Air Force Academy are inspired in different ways. The author was motivated by a statue of a falcon with the following inscription beneath a falcon: "Man's Flight Through Life Is Sustained By The Power Of His Knowledge" [1]. The purpose of this research is to acquire pavement engineering knowledge which can then be represented in a knowledge-based expert system (KBES). This KBES can then be used to solve difficult rehabilitation design problems for airport concrete pavements. Experience-based pavement design will improve aircraft safety and provide an operating surface that will structurally support sustained aircraft flights throughout the pavement's design life.

Sustained aircraft operations are critical not only during war, but also during peacetime. Since air travel has become increasingly popular as a mode of transportation, airports have become increasingly congested. Airlines and airport users may lose millions of dollars if airport operations are disrupted or delayed when a runway, taxiway or apron is closed for repairs. Therefore, it is critical that pavement repairs be made in a timely manner. When repairs are made, the correct repair must be selected and properly designed to minimize the number of future closures for repairs.

1.1 THESIS OBJECTIVES

One of the primary objectives of this research is to acquire expert knowledge for each phase in the selection and design of rehabilitation alternatives for a jointed plain concrete pavement (JPCP) on an airfield. All participants in the overall design process are considered in this research, but the planner and designer are viewed as the key participants. Accordingly, their work receives the most emphasis in this research. The responsibilities and design procedures of the planner and designer vary among agencies. This variance has led to an inconsistent application of basic pavement theory among consultants and agencies such as the U.S. Air Force, the Federal Aviation Administration (FAA), the U.S. Navy and the U.S. Army Corps of Engineers.

Inconsistency in pavement design can be minimized by **unifying expertise in each phase of the design process to form a more complete, comprehensive and permanent knowledge-base than is currently available in government, industry or academia**. One organization may have a wealth of field experience but lack the theoretical expertise which is needed to explain pavement performance in the field. Likewise, another organization may have extensive theoretical expertise, but lack the field experience necessary to validate theoretical research. Until a comprehensive knowledge-base is established, researchers and field engineers will not have a common reference from which to work. Therefore, the second objective of this research is to establish a design standard for airfield JPCP rehabilitation planning and design. A <u>knowledge-base</u> will be the design template which is used to guide future research work in airport design.

Before the acquired knowledge is accepted as a design standard by an agency, the knowledge must be successfully used to complete rehabilitation designs. As confidence in the knowledge-base increases, it will be more widely recognized as a reference point for future advances in pavement design. Thus, the final objective of this research is to demonstrate the successful acquisition and representation of pavement knowledge by solving realistic airfield pavement design problems.

1.2 JUSTIFICATION FOR AN AIRFIELD KNOWLEDGE-BASE

The average lay person usually views a pavement structure as simply "asphalt or concrete placed on top of soil." Indeed, a novice civil engineer can be fooled by the apparent simplicity of a pavement structure. Before planning and designing an airfield repair, civil engineers need formal education courses in pavements and they should have some field experience. Without this preparation, they will almost certainly make costly design errors. Many costly mistakes have been made in airport and highway rehabilitation design and construction. The author makes this statement based on first hand experience as an U.S. Air Force base pavements engineer. Without guidance from several pavement experts in the Air Force, costly mistakes might have been made on several airfield repair projects. This section explains why pavement design is such a challenge, even for the more experienced pavements engineer.

The horizontal structure of a pavement system consists of one or more layers which are designed to distribute wheel loads to protect the soil or subgrade from high stresses and strains. The top layer usually consists of asphalt concrete (AC) or Portland cement concrete (PCC) which have very different material properties. Due to hourly, daily and seasonal changes in moisture conditions and temperatures, many of these properties are constantly changing. Since the top layer is the operating surface for traffic, it must be smooth and provide good skid resistance in all weather conditions in order to be considered "acceptable" to the user.

Aircraft traffic is one of the most difficult variables to estimate in the design of a pavement system. The gross weight, tire pressure and gear configuration of aircraft vary from one aircraft model to the next. These variables significantly affect the amount of structural damage caused by an aircraft. The design problem gets more complicated when several types of aircraft must be considered in the design of a pavement system and traffic loadings must be estimated to determine past or future fatigue damage. In the past, traffic engineers have had little success in predicting future traffic and records of past airfield traffic seldom exist.

Another highly variable component in a pavement system is the subgrade which is the foundation for the man-placed layers. Within the United States, there are more than 12,000 soil series [2]. Except for the "A" horizon, the top layer of soil which is highly organic in nature, each soil in a soil series has similar, but not identical properties. The numerous types of soils and material property variability of a soil make it very difficult to select values for input parameters used in pavement design.

Climate plays a significant role in the design of pavements. The pavement engineer must consider the future impact of climate in a pavement system that has a typical design life of 20 years. Since climates constantly change, the pavement engineer must use statistics to predict the effect of climate on pavement materials. Climatic factors can have a significant impact on the durability, aging and strength of various structural layers, including the subgrade.

The diversity and complexity of pavement design prevents one person from becoming an expert in all areas of this subject domain. Over time, an individual may be known as the expert in a particular subfield of study in pavement engineering. Or, a pavement engineer may develop a general understanding of most areas of pavement evaluation, materials, design and rehabilitation. In the latter case, depth of knowledge must be sacrificed for breadth of knowledge due to the size and complexity of the domain. Therefore, difficult problems in pavement analysis and design are not solved by one engineer, but by a team of cooperating pavement experts.

Pavement rehabilitation design would not be such a major problem if each commercial airport or military airfield had an expert as a pavements engineer. However, this is not a feasible option. For example, the U.S. Air Force has few experienced pavement engineers at its bases. To compensate for this inexperience, an experienced pavement engineer is located at a Major Command which oversees the operation of several Air Force bases. The five largest commands are the Strategic Air Command (25 bases), U.S. Air Forces in Europe (25 bases), Tactical Air Command (18 bases), Military Airlift Command (15 bases) and the Air Training Command (13 bases). Since 1983, when the author was a base pavements engineer, four of the five Major Commands have lost their experienced engineer due to retirement or death. If an expert knowledge-base had been developed, this expertise would still be with the Air Force and be readily available at each base.

1.3 OVERALL APPROACH

The knowledge acquired and represented in this research represents knowledge of key participants in the design process. Sources of this knowledge include textbooks, research papers and most importantly, pavement experts. In 1980, a consultant for the Air Force collected pavement condition, material properties and aircraft traffic data for 189 different JPCP pavement areas at 12 U.S. Air Force bases [3]. These data were used in structured interviews during this research to determine how current and former Major Command pavement engineers use pavement data to select a feasible repair for a JPCP pavement. Current design procedures are integrated with the latest design technology to select material properties and perform rehabilitation designs. KBES methods and techniques were used to represent pavement systems and design procedures.

Object-oriented programming and rules are the knowledge engineering techniques used in this research. Collections of objects are used to represent two components of the entire knowledge-base. The first component describes the tangible and intangible objects of an airfield while the second models pavement behavior. Finally, the decision-making knowledge of the participants in the design process is represented using rules. These knowledge-bases were implemented using Goldhill's expert system tool, Goldworks II [4]. The implementation of these knowledge-bases is titled an "AIRfield PAvement Consultant System (AIRPACS)."

AIRPACS was developed to validate the knowledge acquired and demonstrate the appropriateness of a knowledge-based design approach for the airport pavement design domain. Recommendations made by AIRPACS were compared to several airport rehabilitation design reports from ERES Consultants, Inc., a national pavement consulting firm, and found to be in good agreement. The success of AIRPACS should build design agency confidence in a knowledge-based approach, and provide a base-level of pavement design knowledge for further research in airport pavement design.

1.4 BENEFITS OF A KNOWLEDGE-BASED DESIGN APPROACH

AIRPACS is a powerful design tool because it incorporates both analytical tools and expert engineering judgement. This knowledge-base will provide a rehabilitation design template for future research and allow field engineers to benefit from knowledge that is captured using this design approach. AIRPACS provides the latest airfield pavement technology to every airport, whether that airport supports one or one million annual flights. If the airport has an inexperienced pavement engineer, AIRPACS is an invaluable tool. Airports with an experienced engineer will appreciate AIRPACS since it will quickly solve difficult design problems. For each of these situations, the engineer will have pavement expertise readily available on a daily basis at a fraction of the cost of a reputable consultant. As advances are made in pavement design technology, field engineers can have the knowledge-bases in AIRPACS updated.

1.5 LIMITATIONS

The knowledge acquired and implemented in AIRPACS is for an airfield jointed plain concrete pavement with no overlays. AIRPACS considers all types of rehabilitation alternatives for a JPCP, but it depends on pavement evaluation results which are needed to design each alternative. Since evaluation knowledge-bases are not a part of AIRPACS, the user must enter all evaluation results. In addition, rehabilitation design knowledge for all remaining types of pavement must be added to the knowledge-bases. These include AC pavements as well as other types of PCC pavements such as jointed reinforced concrete pavement (JRCP) and continuously reinforced concrete pavement (CRCP). Future work should also include composite pavements such as PCC pavements overlaid with AC.

1.6 THESIS ORGANIZATION

The remaining chapters of this dissertation are organized as follows.

CHAPTER 2 Provides an overview of the issues in the airfield pavement design process and the knowledge-engineering techniques that are used to represent the design process.

CHAPTER 3 Discusses in detail the JPCP rehabilitation design process and the pavement models that are used in this research.

CHAPTER 4 Describes the implementation of the JPCP design process to form AIRPACS, a knowledge-based design system.

CHAPTER 5 Demonstrates strengths and weaknesses of AIRPACS by solving several realistic rehabilitation design problems.

CHAPTER 6 Summarizes research contributions, limitations and future research and development needs.

CHAPTER 2

BACKGROUND

This chapter introduces basic concepts in pavement engineering, provides an overview of the design issues and presents the knowledge-representation techniques used to develop AIRPACS. The following sections introduce fundamental pavement and expert system terminology that is used in the remainder of this dissertation. A basic understanding of the terminology and concepts will help the readers appreciate the detailed discussions in Chapters 3 and 4 even though they may have only minimal experience in pavement design or knowledge engineering.

2.1 AIRPORT PAVEMENT DESIGN ISSUES

The following discussion focuses on the issues in the design process rather than the mechanics of the design process itself. Material properties, aircraft traffic and climate are all categorical inputs to this process. A general description of each input is given in the following section to facilitate a better understanding of their influence on structural performance and operational safety. Both of these pavement issues are central concerns throughout the design life of an airport pavement, and will be repeatedly addressed throughout this dissertation.

2.1.1 Design Process Inputs

Pavement materials, aircraft traffic and climate evaluation data must be considered for reliable design. Engineers use these data to relate pavement response to pavement performance. The output from any design procedure is meaningless if the data used to develop this design are not carefully collected. Much of these data can be collected by a technician with little pavement expertise. However, the remaining data must be collected and analyzed by an experienced pavement engineer.

2.1.1.1 <u>Pavement Materials</u>

The most common types of pavement structures are constructed using asphalt cement and Portland cement in the surface layer. Engineers commonly refer to these structures as flexible and rigid pavements, respectively. Since this research focuses on JPCP rehabilitation, the following discussion is limited to one type of rigid pavement, jointed plain concrete pavement (JPCP). The primary difference between a JPCP and other types of rigid pavements is the amount of steel reinforcement in the concrete, which controls the spacing between joints in these pavements.

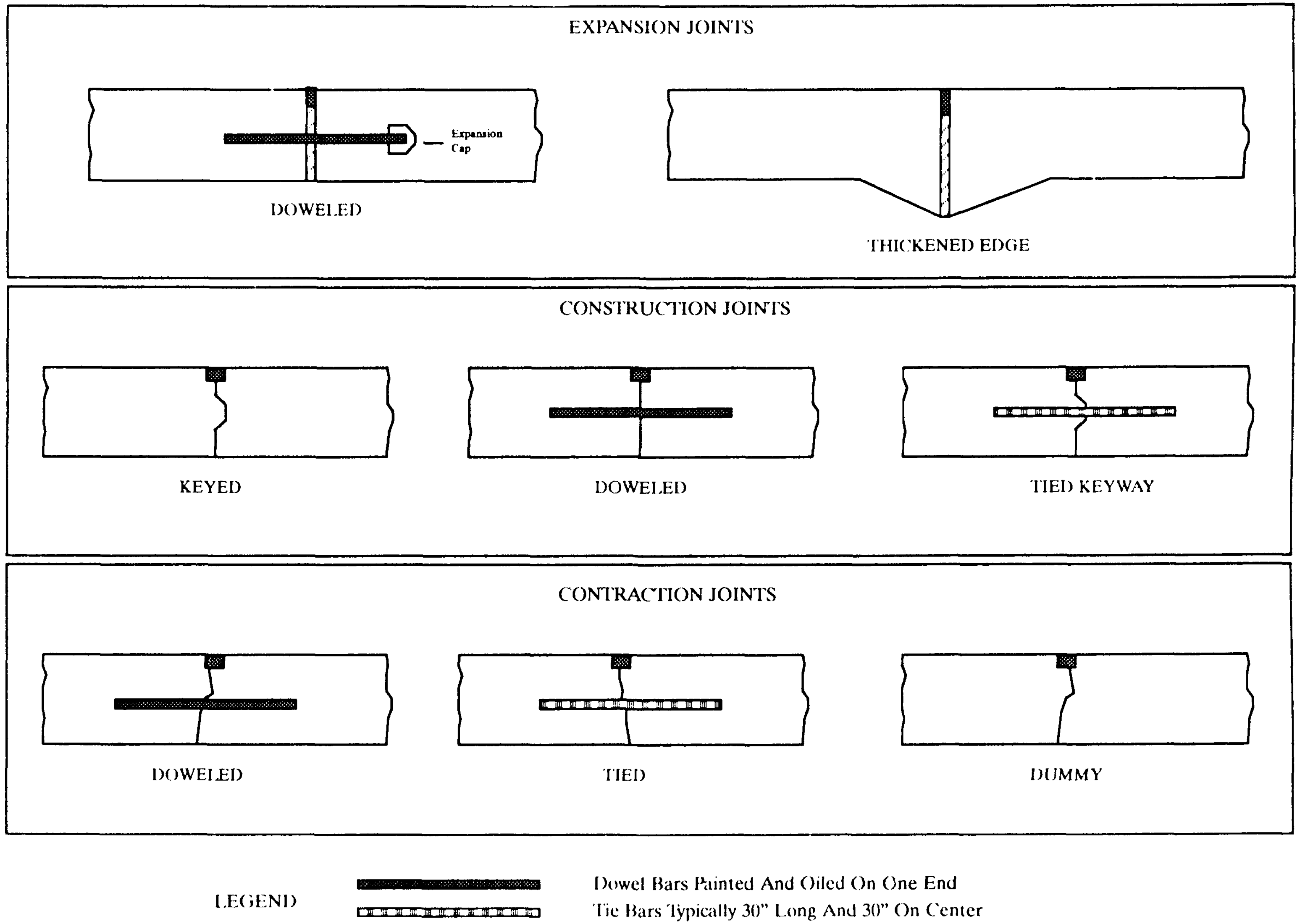
Joints are used to control the location and pattern of cracking in a JPCP. Portland cement pavements without joints will randomly crack because high stresses develop in the concrete when moisture and temperature cause the concrete to expand, contract, curl or warp. Therefore, joints must be used to prevent random cracking of the pavement and make it easier to maintain the pavement. Joints in a JPCP are formed by making sawcuts which are normally parallel and perpendicular to each other. Each of the areas bounded by joints in a JPCP is commonly referred to as a slab. Normally, the length of the slab in a JPCP does not exceed the width by more than 25 percent with the typical joint spacing varying from 12 to 30 feet [5, 6, 7].

There are several types of mechanisms which provide load transfer between slabs as an aircraft's tires pass over the joint (Figure 2-1) [7]. The most frequently used load transfer mechanisms are dowels, keyways and aggregate interlock. Load transfer occurs when an aircraft tire rests on the edge of a slab and a portion of that load is transferred across the joint to the adjacent slab using dowels, keyways or aggregate interlock. Good load transfer reduces the stresses in the slab and greatly extends the life of the pavement. One of the best load transfer mechanisms is the steel dowel.

Steel dowels may be used for expansion, construction and contraction joints as shown in Figure 2-1 [7]. This figure also shows typical dowel bar lengths and installation locations in the concrete. Diameters of the steel dowels range from 3/4 to 2 inches. Larger dowels are used in airport pavements where heavy aircraft loads are encountered. Although keyed joints are not recommended because of possible keyway shear failure, keyed joints often exist in older pavements and are usually constructed as shown in Figure 2-1 [7]. When dowels are not used in contraction joints, aggregate interlock action still provides some load transfer, particularly in hot weather.

The amount of load transferred by aggregate interlock depends primarily on the type of aggregate and the width of the crack in the joint. Larger aggregate

FIGURE 2-1
JPCP JOINT TYPES



with angular faces is much better than smaller aggregate with smooth faces. The width of the crack depends on several factors, but temperature has the greatest effect. On a hot day, the joint closes and the load transfer is much higher than it would be on a cold winter day. Thus, the amount of load transferred by aggregate interlock is very dependent on temperature, which changes daily and seasonally, and on aggregate angularity.

A JPCP may be constructed on a granular or stabilized base layer, or constructed directly on the subgrade soil. The primary functions of a base for PCC pavements are to provide a construction platform for equipment; to help keep the structure free of excessive moisture; to help protect against frost damage and to provide uniform support conditions for the concrete slab. The most common types of binding agents in a stabilized base include lime, Portland cement and asphalt. Although a stabilized base has little permeability, an unbound base may also be relatively impermeable if the base has a high percentage of clay and silt particles.

In most cases, a stabilized base prevents erosion and pumping better than an unbound base. Erosion is the loss of support beneath the concrete slab which usually occurs through the pumping of water. Pumping occurs when an unbound base or the subgrade is saturated. As the wheel travels across the pavement, the slab deflects, forcing water and fines up through the joint and onto the pavement surface. If a sufficient amount of erosion occurs in the base or subgrade, a void will be created between the concrete slab and the base. This leads to much higher deflection stresses in the slab and early structural failure.

The amount of water entering the base and subgrade from the pavement surface is reduced by sealing the joints in the pavement. However, the primary benefit of the joint sealant may be to prevent incompressible material from entering the joint. If incompressible material enters the joint reservoir over a number of years, the surface of the pavement may experience a shear failure as the slab expands when the temperature increases. This failure, known as spalling, could progress to the state where the entire cross section of the slab fails in shear. The latter form of failure is referred to as a "blow-up" and requires an emergency repair before traffic operations resume.

The preceding discussion focused on the material components of a JPC pavement. Each component was introduced by discussing its function in the JPCP system. JPC pavements have a short joint spacing to prevent cracking since there is no steel reinforcement in the concrete to hold cracks tightly together. Since there are a large number of joints in a JPCP, load transfer across joints is a critical issue. The foundation of a JPCP is the subgrade and base course which provide a platform for construction equipment and a structural foundation for those aircraft that use the pavement. Before one can appreciate the pavement and aircraft interaction, it is important to understand those aircraft characteristics that are considered in the pavement design process.

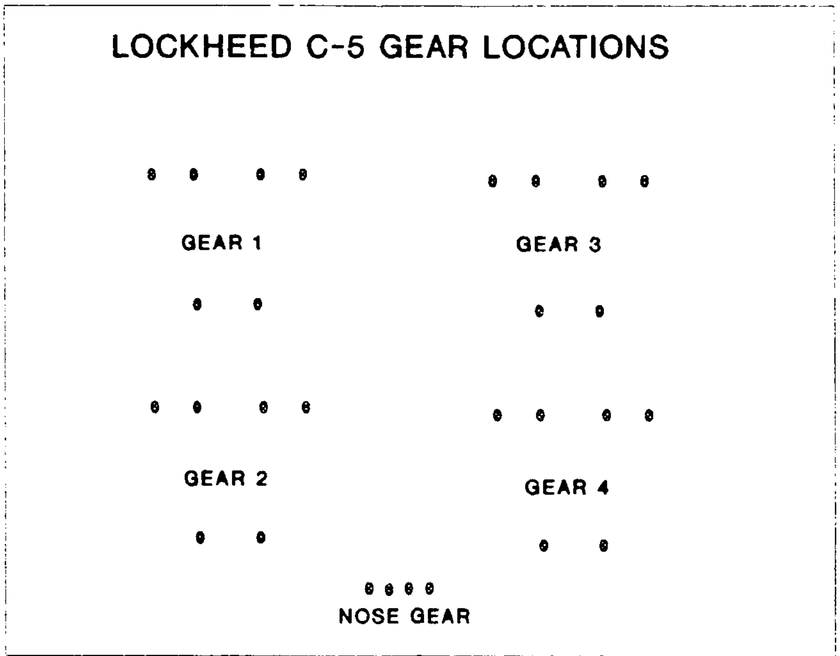
2.1.1.2 Aircraft Traffic

Aircraft owners, such as commercial airlines and the U.S. Department of Defense, are primarily concerned with aircraft payloads and safety. As pavement users, these organizations are satisfied when they can load their aircraft as they wish and have a safe operational surface. Pavement engineers must address both of these operational concerns when they are analyzing past, present and future pavement performance. Aircraft payloads are a major concern to the pavement engineer because history has shown that aircraft are often modified to increase the payload capacity of the aircraft. Since aircraft gear and tire configurations are seldom redesigned during the modification, the resulting increase in gear loads and tire pressure will create more pavement damage. This section describes those aircraft characteristics that provide key inputs in the assessment of pavement performance.

Aircraft characteristics will be introduced by comparing two aircraft which have similar gross weights, but cause significantly different amounts of pavement damage. Lockheed's C-5B cargo plane has a maximum gross weight of 840,000 lbs while Boeing's B-747-300 has a maximum gross weight of 833,000 lbs. The difference in weight is less than 1 percent, but the key issue is how the weight is distributed to the pavement surface. Each aircraft has one nose gear and four main gear assemblies as shown in Figure 2-2. In addition, the gross weight distributed to each gear is similar as shown in Table 2-1. But this is where the load distribution characteristics begin to differ.

Figure 2-3 shows the number of tires on each gear and the spacing of the tires. The C-5B has six tires distributing the gear load while the B-747 has only four tires. In addition, the C-5B and B-747 have tire contact areas of 297 in^2 and 237.5 in^2 per tire, respectively. Tire number and contact areas result

FIGURE 2-2
C-5 AND B-747 GEAR COMPARISON



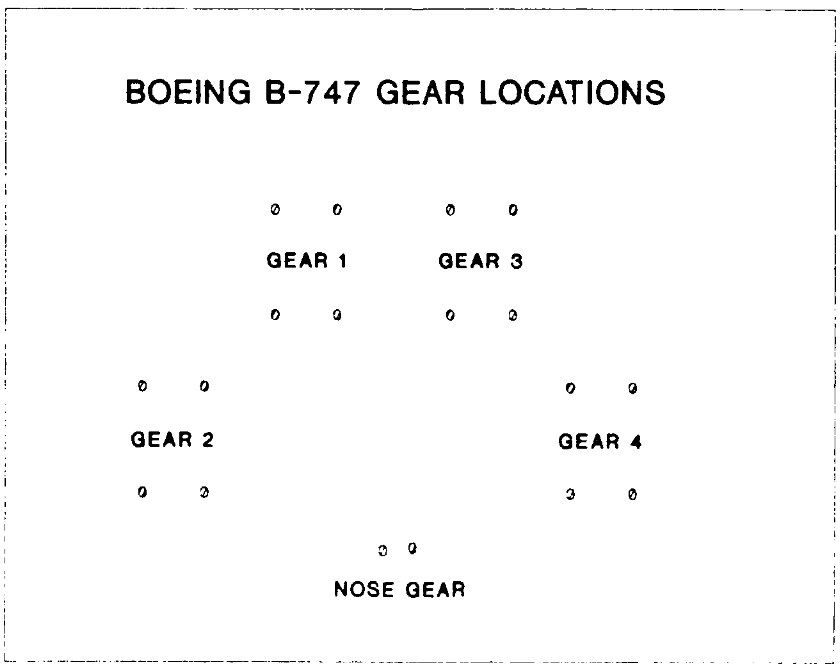
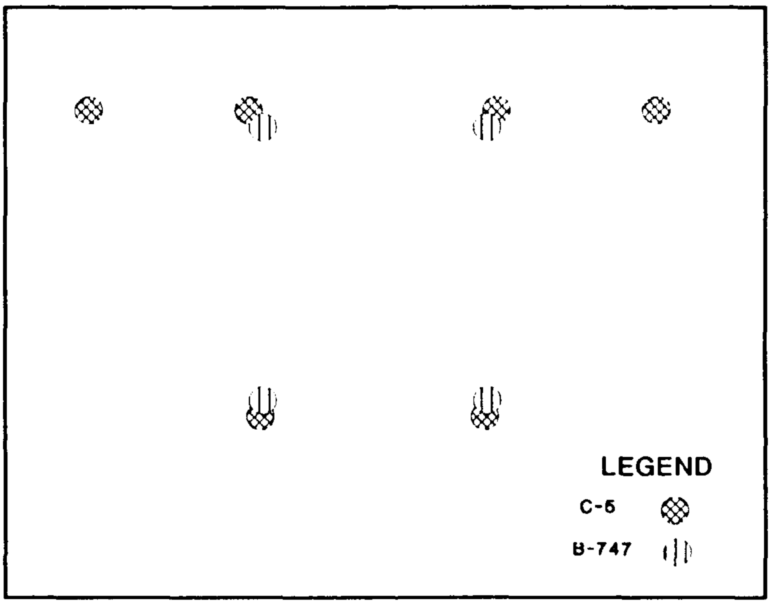


TABLE 2-1
B-747 AND C-5B GEAR ASSEMBLY LOADS

AIRCRAFT	MAIN GEAR WEIGHT (lbs)	NOSE GEAR WEIGHT (lbs)
C-5B	197,000	48,000
B-747-300	194,600	54,200

FIGURE 2-3
B-747 AND C-5B MAIN GEAR TIRE LOCATIONS



in respective contact pressures of 111 and 210 psi for the C-5B and B-747. Boeing's B-747 also causes more damage to the pavement since the tires are not spread out over as large an area as those of the C-5B, as shown in Figure 2-2.

The B-747 does have a more favorable pass-to-coverage ratio. When pilots take off or taxi an aircraft, they attempt to keep the aircraft centered on the runway or the taxiway. The amount a pilot wanders from the centerline is very important since wander directly effects the amount of damage a pavement will sustain after several aircraft passes. When the aircraft is travelling very fast during takeoffs on a runway, the standard deviation of the wander is approximately 60 inches. Likewise, the standard deviation is 30 inches on a taxiway where the aircraft is moving relatively slow [8]. This means that a point on the pavement in the wheel path of an aircraft is loaded more frequently if the pavement facility is a taxiway as opposed to a runway. The number of times an aircraft must pass along a pavement facility before a particular point is covered is known as the pass-to-coverage ratio at that point. In addition to aircraft wander, the ratio also depends on the type of main gear and the main gear location.

Pass-to-coverage (P/C) ratios for the mean gear location in the wheel path can be as high as 33 for fighter aircraft or as low as 1.5 for the C-5B cargo aircraft operating on a taxiway. Runway P/C ratios for a B-747 and C-5B are 6.14 and 1.89, respectively. Lockheed's C-5B has a lower P/C ratio for two reasons. First, the main gear are located directly behind each other in contrast to the B-747 as shown in Figure 2-3. Another reason the C-5B P/C ratio is lower is that it has more main gear tires and the width of each tire is larger. Despite the fact that the C-5B's P/C ratio is much lower, the B-747 will create more pavement damage if the number of passes of each aircraft is equal. As a result, a typical thickness for a doweled JPCP might be 8.5 inches if designed for the C-5B and 11.5 inches if designed for the B-747 operating on a taxiway. If a JPCP is 11.5 inches thick and the aircraft gear are placed on the transverse joint, a typical free edge stress would be 450 psi for the C-5B and 870 psi for the B-747.

The preceding discussion described aircraft characteristics which affect load distribution to the pavement, but the engineer is also concerned with Foreign Object Damage (FOD). Pavement debris, such as joint sealant and spalled concrete, can be ingested by aircraft engines, cut tires, or damage the skin of the aircraft. Much research has been conducted to determine why certain aircraft have higher unscheduled engine removal (UER) rates (i.e. an apparent greater susceptibility to FOD). Factors that have been reviewed include engine inlet diameter, engine height above the pavement surface and mounting location of engines [9]. However, these research efforts have only led to a qualitative description of the principal damage mechanisms. These mechanisms include projection of debris from landing gear and ingestion of debris by way of the engine inlet vortex [9]. These mechanisms are discussed in more detail in Chapter 3.

The design process would be less complicated if the only interactions were those occurring between the pavement structure and the aircraft. However, the complexity of pavement system interactions is significantly increased when climatic characteristics are added to the materials and aircraft traffic inputs.

2.1.1.3 Climate

Pavement engineers must carefully consider the climate since it significantly affects pavement performance and aircraft safety. Engineers are primarily concerned with pavement exposure to varying amounts and physical states of moisture, freeze-thaw damage to PCC, thermal gradients in the PCC slab, frost penetration into the subgrade and the number of freeze-thaw cycles in each structural layer. The climatic elements of sunshine, wind, rain, snow, ice, temperature and temperature changes all affect these areas of concern. Since most people are familiar with weather terminology, no further explanation of climate is given.

One of the critical issues in rehabilitation design is the interaction of pavement materials and climate. Chapter 3 will explain the JPCP distresses that may develop from this interaction. The next issue in this chapter is how a pavement responds when an external load is applied to the pavement surface, and how this behavior changes after years of exposure to the climate.

2.1.2 Pavement Response To Aircraft Loads

As an aircraft gear travels across a pavement, the pavement structure deflects in the vicinity of the gear and experiences various magnitudes of stress and strain. Deflection, stress and strain are the basic types of pavement responses. The magnitude of each of these responses depends on the gear load and the amount of time the load is applied to the pavement.

Pavement responses are higher for an aircraft "holding" on a taxiway than they are for that same aircraft taxiing at high speed on the same taxiway. The magnitude of pavement stress, strain and deflection, and the number of load repetitions at each of those response levels must be sufficiently low to prevent early concrete failure. Failure may occur when the flexural stress in the concrete exceeds the ultimate strength of the concrete; however, the more common mode of failure in pavements is fatigue. This type of failure occurs when the pavement is repetitively loaded at a stress level lower than the ultimate concrete strength [10, 11].

For most airport pavements, one or two types of aircraft cause 90 percent of the concrete fatigue damage. These aircraft are known as the critical aircraft in the design process. The engineer must insure that the operational weight of the critical aircraft will not cause premature structural failure of the pavement. For existing pavements, past and future fatigue damage must be considered before the engineer knows if any structural improvements are needed.

Concrete cracking is the most common visible indication of pavement fatigue damage. Slab corner breaks, longitudinal cracks, transverse cracks and diagonal cracks which systematically occur throughout the pavement facility in trafficked areas are clear signs of structural failure. With the exception of corner breaks, most of these cracks begin at the bottom of the JPC layer and propagate to the surface. If the pavement is relatively new, the surface may not be cracked or show any signs of fatigue damage. In this case, the engineer must estimate the past damage by reviewing the types of aircraft that have used the pavement facility and the average number of annual departures. This would be an easier task if the ultimate strength of PCC did not change with time, but this is not the case [12].

Just as aircraft traffic changes during the life of the pavement, so do the material properties of the JPC layer. The stiffness and strength of PCC usually increase with age, but the local climate may adversely impact certain concrete material properties. Two of the most common types of concrete durability problems include alkali-silica reactions and "D-cracking". Alkali-silica reactions occur between certain types of aggregate and cement in the concrete. Serious reactions result in a total breakdown of the matrix structure in the concrete. D-cracking is most prevalent in wet climates where the pavement experiences several freeze-thaw cycles. Pores in the aggregate absorb moisture causing the aggregate to expand and contract during a freeze-thaw period. If serious durability problems exist, serious FOD may develop and the JPCP may provide little structural benefit for future aircraft traffic.

A foundation may provide structural support for the JPC layer, but the engineer's primary concern is <u>uniform</u> slab support. Non-uniform support conditions significantly increase the difficulty of the analysis since the area of non-support continuously changes and is not visible. Non-uniform support may develop if the JPC layer experiences foundation frost heave, settlement or erosion. This behavior can be controlled by insuring that the subsurface drains freely, the base is not frost susceptible and the pavement layers limit the depth of frost penetration into a frost susceptible subgrade. Besides reducing the load-carrying capacity of the pavement, foundation problems may also cause roughness and create a safety hazard for aircraft.

2.1.3 Aircraft Safety

An airport pavement enhances aircraft safety if the JPCP surface provides good skid resistance, a smooth surface and has little surface debris. Nothing is more important than aircraft safety! For some types of passenger aircraft, hundreds of lives are at risk during takeoff or landing. During takeoff, these aircraft are fully fueled and traveling at high speeds. If a pavement surface is smooth, has no spalls that could cause a tire to rupture, has good friction characteristics and has no surface debris that could damage an engine, the pavement engineer has done everything possible to ensure that the surface is operationally safe.

A pavement surface is considered smooth if the amplitude of long and short wavelength roughness is so small that pilots and passengers do not notice any roughness during normal aircraft operations. Most long wavelength roughness problems are built into the pavement during construction. Long wavelength roughness is usually noticeable on a runway where aircraft are moving very fast, but short wavelength roughness may be evident on any type of pavement facility. Aside from passenger discomfort, severe surface roughness may make it difficult for pilots to read their instruments, increase the number of cut tires, or worse yet, result in a blown tire during takeoff or landing. Roughness may also cause a problem if it occurs near the point of aircraft rotation during takeoff on a runway. For some aircraft, this could cause a temporary liftoff and extend the distance required for takeoff.

A more frequent safety problem is hydroplaning which can happen on a runway, taxiway or apron. Most hydroplaning problems develop on a runway where both dynamic and viscous hydroplaning can occur. Dynamic hydroplaning depends on the pavement surface macrotexture, aircraft speed, tire pressure and gear configuration. Viscous hydroplaning may develop when the aircraft is moving slow and is primarily a function of the surface microtexture. Microtexture is what makes an aggregate smooth or rough to the touch while macrotexture depends on the PCC surface finish (i.e. grooving, burlap finish, etc) [13]. Macrotexture and microtexture characteristics may change over time through surface wear or the buildup of tire rubber in touchdown areas of a runway. Good surface texture is even more important if the surface does not have adequate longitudinal or transverse slope.

Another safety concern is the amount of pavement debris on a pavement surface. Pavement FOD material includes loose joint or crack sealant, aggregate, and loose concrete. As a sealant ages, it becomes brittle and does not adhere to the concrete. When a JPCP joint loses some of its sealant, incompressible material may enter the joint which eventually leads to joint spalling. Spalling also occurs in pavements that have cracked slabs. As the crack deteriorates, the amount of loose concrete generated by spalling increases. Loose concrete is also generated when the concrete has severe durability problems. In this case, the entire concrete surface may scale or spall off from the underlying sound concrete. All these potential sources of pavement FOD must be kept under control to enhance aircraft safety.

2.1.4 Feasible Rehabilitation Alternatives

This research focuses on rehabilitation options for a JPCP structure that has not been overlaid since original construction. The preceding discussion focused on the issues of design inputs, pavement response under an aircraft load and aircraft safety. The next logical issue to discuss is what repairs correct the various types of JPCP distresses. A feasible alternative should support current and future aircraft operational weights while allowing those aircraft to safely use the pavement facility.

If the pavement will not structurally support future aircraft traffic, there are three feasible strategies. The engineer and airfield manager may decide to (1) do nothing and let the pavement fail early, (2) do nothing to the pavement but reduce the number of aircraft departures to extend the pavement life, or (3) structurally improve the pavement. The load-carrying capacity of the pavement can be increased by placing an overlay on the existing JPCP or by reconstructing the JPCP. If an overlay is placed, both the overlay and existing JPCP contribute to the load-carrying capacity of the modified pavement structure. Since reconstruction usually involves removal of the existing JPC layer, the new JPC structure provides 100 percent of the load-carrying capacity. Increasing the structural capacity of airport pavements is the key factor that allows airports to increase their operational capacity.

If safety improvements are necessary, the JPCP surface must be modified or overlaid. Repairs are made in local problem areas or over the entire surface of the pavement facility. If a structural overlay is needed, this option will also correct any existing roughness, hydroplaning or FOD problems. Otherwise, a thinner overlay may be installed to correct these safety problems. Grinding, slab jacking and slab replacement may be used to correct localized problems such as short wavelength roughness. Finally, grooving can be used to reduce hydroplaning problems if surface macrotexture is poor. Rubber removal in the landing areas of a runway may also improve the surface texture and reduce hydroplaning potential. Hydroplaning problems can be further reduced by insuring that adequate slope quickly removes surface and subsurface free water from the pavement structure.

Drainage improvements will enhance pavement structural performance and aircraft safety. Improvements include longitudinal and transverse JPCP slope increases, permeable base installation (in conjunction with reconstruction), existing drainage pipe repair and new drainage pipe installation. JPCP grade corrections improve surface drainage and reduce hydroplaning potential. Drainage pipe and permeable bases help to remove excessive moisture from the subsurface layers. Drainage improvements also help prevent erosion and pumping, and minimize pavement damage from frost heave or freeze-thaw action.

A JPCP may support future aircraft traffic without compromising safety, but periodic maintenance is still required throughout the design life. Maintenance work includes resealing joints and cracks, partial-depth and full-depth repairs of slabs and slab replacement. For most types of JPCP distresses, more than one maintenance alternative is feasible. This allows the pavement engineer to make expedient repairs or more permanent repairs if time permits. In either case, the objective is to maintain an acceptable rate of deterioration in the JPC pavement without sacrificing safety.

2.1.5 Construction Ease and Expediency

Although an alternative may correct a structural problem or improve operational safety, it may not be a good choice if it requires more time to build than is available for construction. Most airport pavement facilities are too important to be closed for an extended period of time. Therefore, construction periods are kept as short as possible. Fast track construction will reduce facility downtime, but may be prohibitively expensive. Finally, the construction season may have a significant impact on the length of the construction period.

If the pavement is being reconstructed, the base and subgrade are exposed to the weather. If an existing base course is not saturated, it may provide a good platform for construction equipment and minimize weather related construction delays. Many older JPCP pavements, especially those on U.S. Air Force airfields, were constructed without a base course. For these pavements, rains could significantly delay reconstruction if the area does not have good natural drainage. Although soil stabilization methods can be used to decrease delays, they significantly increase construction costs. Weather-related construction delays should be carefully considered in the rehabilitation design process.

2.1.6 Safety During Construction

Most of the interconnected pavement facilities on an airport are too important to be totally closed during construction. Since closing an airport during construction is seldom a viable option for civilian or military airports, aircraft are forced to taxi around construction sites. Alternate taxi routes should keep the aircraft a safe distance away from the work area. However, in some situations the aircraft must operate very close to the work site. In this situation, aircraft operations must be carefully scrutinized to insure worker and aircraft safety are not compromised.

Two of the most important safety concerns for a worker are noise and aircraft accidents. An airport is a very noisy place, especially on military bases that have fighter aircraft. More important than noise are the lives that are at risk when the construction site is close to an active runway. The vast majority of aircraft accidents happen during take-offs and landings. For repair work located in these areas, alternatives with short construction periods are very attractive.

Construction work near a runway also places the aircraft at risk. For most types of pavement repairs, bulky equipment is needed at some point during the repair. If a pilot loses control of the plane during takeoff or landing and crashes into construction equipment, the number of lives lost and the amount of aircraft damage may be high. When pilots are taxiing around construction sites, the primary safety concern is FOD. Certain repairs generate much more pavement debris. Although sweepers keep the work area clean most of the time, engine FOD is still a safety concern of airfield managers.

2.1.7 Traditional JPCP Thickness Design

Selecting materials, determining JPC layer thicknesses and selecting joint spacings are traditional thickness design activities. Many pavement design procedures that are used today include both empirical and mechanistic concepts. Each of these concepts uses a different philosophy to predict pavement performance. However, with the current state of pavement technology, most design procedures use a combination of empirical and mechanistic concepts.

Before the dawn of the computer, most pavement design procedures were empirical in nature. Today, many steps in a design process still have an empirical basis. The most classic use of this methodology is the pavement overlay equations that were developed by the Corps of Engineers [6, 7, 14, 15]. These equations are used to determine the thickness of an AC or PCC overlay constructed on a JPC pavement. Full-scale tests of rigid pavements conducted between 1943 and 1973 were the basis for the overlay equations. The equations are empirical since they do not relate pavement response to pavement performance. Instead, overlay thickness is based on existing JPC layer thickness, existing JPCP condition and the JPC layer thickness that would be required if a new pavement were constructed on the existing foundation.

The most frequent use of mechanistic design is the determination of a JPC layer thickness for a new pavement. For a given concrete flexural strength, engineers determine if a trial thickness has acceptable stress and deflection levels when loaded by the design aircraft. Pavement responses, such as stress and deflection, are much easier to compute quickly now that the computer is readily available to most engineers. Thickness design in a mechanistic procedure is based on the stress ratio, which is the ratio of the slab flexural stress to the concrete flexural strength or vice-versa. As the stress ratio decreases, the number of allowable load repetitions increases. After the stress ratio is determined, the designer estimates how many aircraft passes the pavement can withstand before a critical amount of fatigue damage occurs.

The stress ratio is the only variable used to estimate the number of allowable load repetitions before the pavement fails. However, this is a <u>very</u> difficult transition to make since flexural strength changes as concrete ages.

Most engineers use the results from the Corps of Engineers full-scale tests to empirically estimate allowable repetitions to failure. JPCP failure is normally defined as the number of load repetitions that will, on the average, produce cracks in 50 percent of the slabs. Until better theoretical fatigue models are developed, pavement engineers will continue to correlate stress ratio to JPCP failure.

2.1.8 Future Performance of Rehabilitation Alternatives

Once materials have been selected, structural thicknesses have been determined and joint spacings selected, the next stage in the design process is to predict how the pavement will perform after an alternative has been constructed. A rehabilitation alternative usually corrects more than one pavement distress, or at the very least, minimizes the severity of these distresses. Performance prediction is necessary to estimate the service life of the pavement so an economic analysis can be used to select the most cost-effective repair option. Cost-effectiveness is most frequently quantified in terms of (1) the pavement condition throughout the design life or, (2) the equivalent uniform annual cost (EUAC).

Pavement surveys are often conducted at regular intervals to monitor the pavement condition. Pavement performance can be graphically illustrated in terms of pavement condition versus time. The area under this curve is often described as the performance of the pavement [16]. Rehabilitation will improve the pavement condition which increases pavement performance. Statistical models are often used to predict how a repair will change the current rate of deterioration. Since statistical models that predict pavement performance often depend on large databases, which may not be available, it may be easier to estimate service lives and then compute the EUAC of each alternative.

For many types of rehabilitation options, a typical service life is estimated so an economic analysis can be performed. For example, experienced pavement engineers know how often various types of joint sealant have to be replaced. But it is much harder to estimate the typical service life of a structural overlay. Most engineers who assume a new overlay will safely support future aircraft loads throughout the user-specified design life, are not fully considering climatic effects. Since reliable statistical models may not be available, the best method of predicting performance for an airfield pavement may be a combination of the two approaches just described.

2.1.9 Economic Analysis

The final step in the design process is an economic analysis which helps select a preferred JPCP rehabilitation alternative. Regardless of the approach used to predict performance, the EUAC is a commonly used economic analysis tool. If the pavement condition versus time curves and the EUAC are known, users will be more confident when they select a rehabilitation alternative. Ideally, the alternative selected will be within or close to the project budget.

2.2 KEY PLAYERS IN THE DESIGN PROCESS

With a general understanding of the issues in the design process, it is helpful to understand how the various design responsibilities are delegated. Two organizations that are actively involved in the airport pavement design process are the U.S. Air Force and the Federal Aviation Administration (FAA). As an airfield user, the Air Force performs a majority of the design responsibilities in-house. On the other hand, the FAA primarily acts as a consultant to the various privately and municipally owned and operated commercial airports.

2.2.1 Key Players In The Air Force Design Process

The three organizational levels involved in the design process include the Air Force Headquarters, Major Commands (MAJCOMs) and Air Force Bases. Most of the design activity occurs at the base level with technical guidance and funding approval coming from the MAJCOMs and the Air Force Headquarters.

The Air Force headquarters approves operations and maintenance (O&M) budgets and expensive new construction and rehabilitation projects. Expensive projects usually involve a mission change where the existing airfield pavement facilities cannot support the new aircraft. Examples include deployment of the new B-1 bomber or relocation of heavy cargo aircraft to bases that currently support only light fighter aircraft. If technical assistance is needed at the Air Force level, planners and programmers turn to the Major Command's pavement engineer.

The MAJCOM's pavement engineer usually has more pavement experience than anyone else at the MAJCOM or base level. This person usually has 10 to 30 years of pavement experience and has a Bachelor of Science degree in engineering. Since most of these engineers have spent their entire career in the field, few have had the opportunity to get an advanced degree. However, they are highly respected at all levels in the Air Force because of their experience. Although their primary responsibility is to provide technical guidance, the MAJCOM pavement engineers' approval of a project is usually needed before a project is funded.

Since the MAJCOM pavement engineers provide technical guidance for as many as 25 bases, they do not have time to get involved with individual project designs at each of the bases. Most of this work is done by the Base Civil Engineering (BCE) organization. However, fewer and fewer BCE organizations are fortunate enough to have a pavement engineer. In most cases, pavement design is one of several responsibilities of a civil engineer. If a problem is too difficult for the BCE organization, a consultant must be hired to evaluate and design the project. When funds for consulting services are limited, the project is often delayed unless an emergency exists.

2.2.2 The Federal Aviation Administration's Design Role

The FAA's role is primarily one of technical support for commercial airports in the country. Since there are such a large number of private and municipal airports in the United States, design manuals provide most of the technical support. These manuals reflect the philosophy and expertise of FAA engineers. Two of the publications that are frequently mentioned in this research include Aircraft Data (AC 150/5325-5C) [17] and Airport Pavement Design And Evaluation (AC 150/5320-6C) [7]. A list of several other FAA publications is shown in Appendix A. If any of these publications needs revision, the FAA may hire a consultant, such as the U.S. Army Corps of Engineers. Much of the Corps of Engineers research is reflected in the FAA publications, including the empirical overlay equations previously discussed.

The preceding discussion focussed on key players who are involved in the traditional planning and design phases of the overall design process. Other players include ground safety officers on Air Force Bases, airport managers and potential contractors. Inputs from each of these individuals may significantly affect JPCP construction and performance throughout the design life. The following sections describe the methods of representing the knowledge of all players who make a contribution in the airport pavement design process.

2.3 KNOWLEDGE ENGINEERING TECHNIQUES

One has to understand the various types of knowledge used in solving a problem before choosing the methods for its representation. Knowledge can be a structured group of facts in a domain (i.e. a car has four wheels and an engine). Another type of knowledge might model how we make decisions. This type of knowledge is used when a mechanic uses a checklist to decide why the engine will not start. These types of knowledge come from a variety of knowledge sources.

The sources of knowledge distinguish a simple knowledge-based system (KBS) from a knowledge-based expert system (KBES). If the source of knowledge is from a recognized expert in the subject domain, the heuristics and judgement represented in the KBES are likely to be correct and efficiently lead to a solution. AIRPACS knowledge sources are engineering leaders from universities and the Department of Defense. This research uses theoretical and field expertise to formalize a comprehensive design approach to airfield pavement rehabilitation.

2.3.2 Knowledge Representation Techniques

Rules and objects are the primary methods of representing knowledge in this research. Objects represent domain structure while rules represent decision-making knowledge and heuristics [18, 19, 20]. A good ES tool will include both of these paradigms since each is more efficient at representing one type of knowledge. For this reason, rules and objects complement each other very well and make knowledge representation more natural if both are used in a KBES. The power of an ES tool is measured by the number of features and flexibility built into a paradigm. Since Goldworks II was used in this research, Goldhill Computer Inc. terminology is frequently used throughout this section to describe the features of rules and objects.

2.3.2.1 Objects

In an object-oriented representation, any tangible item or abstract concept is an object. Genesereth states that the formalization of knowledge in declarative form begins with a conceptualization that includes objects that exist in the world and their interrelationships [21]. These relationships are often described using semantic nets or frames [19, 22, 23]. Each object in a network can be described by a set of attributes and procedural attachments that describe the behavior of that object [19, 22, 23, 24].

Objects that have similar attributes and behavior are often grouped together to describe a **class** which is represented as a node in semantic nets or frames. In addition, there can be subclasses of a class object which inherit the attributes and behavioral characteristics of that object and all superclasses of that parent object. A class object provides a data and behavioral template for **instances** of that object. Each instance will inherit the attributes or **slots**, slot default values, and the procedural attachments of a class.

Procedural attachments are sometimes described as **daemons** which are activated when certain events occur. A daemon may be activated when the value of a slot in an instance changes or when that value is accessed. Procedural attachments allow the knowledge engineer to manipulate the data of an object instance or move data between instances [23]. Each type of slot behavior that is used in this research can be explained better through an example problem.

Lets assume a vehicle rental company wants to develop a KBES to improve maintenance operations of its fleet. The company's fleet includes all sizes of automobiles and minivans. Engines and tires are the primary maintenance concerns of the company. Mileage, number of rentals and the mean number of miles driven per rental are key factors the company uses to schedule maintenance. Since these factors also describe a typical rental vehicle, they are included as slots in the vehicle class shown in Figure 2-4. Mileage will always be a numerical value and will never be greater than 50,000 since the company always sells vehicles before they accumulate this amount of mileage. Therefore, this slot value will be restricted to the **range** of 0 to 50000 to prevent an erroneous input to the KBES.

In addition to constraints placed on the mileage slot, the slot could be instructed to perform an action if the value is accessed or modified. In this example scenario, the rental company is interested in the average number of miles the vehicle has been driven each time it is rented. When a vehicle is returned, the KBES user inputs the new total mileage. At that time, a **when-modified** facet of the mileage slot would activate a daemon, which is a function containing instructions to do something [4]. The daemon would increase the "number-of-rentals" slot by one, compute the new mean mileage per rental and update the value in the "mean-mileage-per-rental" slot.

FIGURE 2-4
VEHICLE TOP-LEVEL CLASS EXAMPLE

SLOTS	CONSTRAINTS	DEFAULT-VALUE
Vehicle-Type	Auto OR Minivan	Auto
Front-Wheel-Drive	Yes OR No	Yes
Mileage	0 to 50000	0
Number-of-Rentals	Number	0
Mean-Mileage-Per-Rental	Number	0

VEHICLE

Besides the vehicle class, classes of objects must be defined to describe the parts (i.e. engine and tires) of the vehicle that will receive scheduled maintenance. Lets assume the rental company purchases it vehicles from two manufacturers, Ford and Chrysler. All engines in automobiles are manufactured by their respective vehicle manufacturer, but a Chrysler minivan has either a Chrysler or Mitsubishi built engine. Chrysler installs Goodyear tires on all their vehicles, but Ford installs Michelin and BF Goodrich tires on their cars and Goodyear tires on their minivans. Finally, only Chrysler makes front-wheel-drive vans, but both manufacturers make front-wheel-drive and rear-wheel-drive cars.

Using manufacturer information as a guide in further defining our structured KBES, another top level class is created as shown in Figure 2-5. The maintenance-part class is used to make it easier to create the engine and tire class objects shown in Figures 2-6 and 2-7. The manufacturer slot which is **inherited** from the maintenance-part class is shown again in Figures 2-6 and 2-7 since different constraints apply for an engine and a tire [4].

The behavior of the "mileage" slot of the "Maintenance-Part" class shown in Figure 2-5 is different than the behavior of the same slot of the "Vehicle" class shown in Figure 2-4. A when-modified daemon attached to the "mileage" slot of the "Maintenance-Part" class watches the value of the "mileage" slot of "Vehicle" class [4]. If the slot value in the "Vehicle" class changes, the daemon will compute the mileage driven during the past rental and add that mileage to the existing mileage in its own slot. This behavior allows the rental company to maintain accurate records of the mileage on each vehicle part. For example, one tire on a vehicle may have blown so the new tire will have less mileage than the vehicle.

Now that the KBES structure and behavior have been defined, instances can be created for each vehicle in the rental company's fleet. In addition, instances can be created for each vehicle's engine and tires. If the company has 3 Dodge Caravan LE minivans, one of the vans might be represented as an object as shown in Figure 2-8. Figures 2-9 and 2-10 show the engine and tire instance objects which are part of the Dodge-Caravan-LE-2 instance defined in Figure 2-8.

Additional vehicle, engine and tire instances would be created for their respective object class until the entire fleet is represented. The end result is a natural representation of all pertinent facts about all vehicles owned by the rental company. Instance objects can easily be added or deleted when the company decides to sell or purchase a vehicle. If the structure of the object classes is carefully constructed, it will be much easier to define rules that use information in the structure.

FIGURE 2-5
MAINTENANCE-PART TOP LEVEL CLASS EXAMPLE

SLOTS	CONSTRAINTS	DEFAULT VALUE
Part-Of-Vehicle	Vehicle Instance	
Manufacturer		
Mileage	Number	0

MAINTENANCE-PART

FIGURE 2-6
TIRE CHILD CLASS OF MAINTENANCE-PART EXAMPLE

SLOTS	CONSTRAINTS	DEFAULT-VALUE
Type	Steel-Belted OR Bias-Ply	Steel-Belted
Manufacturer	Goodyear, BFGoodrich OR Michelin	Goodyear

TIRE

FIGURE 2-7
ENGINE CHILD CLASS OF MAINTENANCE-PART EXAMPLE

SLOTS	CONSTRAINTS	DEFAULT VALUE
Manufacturer	Ford, Chrysler OR Mitsubishi	Chrysler
Size	V4, V6 OR V8	V6
Fuel-System	Fuel-Injection OR Carburetor	Fuel-Injection

ENGINE

FIGURE 2-8
VEHICLE INSTANCE

SLOTS	SLOT VALUE
Vehicle-Type	Minivan
Front-Wheel-Drive	Yes
Mileage	20000
Number-of-Rentals	60
Mean-Mileage-Per-Rental	333

DODGE-CARAVAN-LE-2

FIGURE 2-9
ENGINE INSTANCE

SLOTS	SLOT VALUE
Part-Of-Vehicle	Dodge-Caravan-Le-2
Manufacturer	Mitsubishi
Size	V6
Fuel-System	Fuel-Injection
Mileage	20000

LE-2-ENGINE

FIGURE 2-10
TIRE INSTANCE

SLOTS	SLOT VALUE
Part-Of-Vehicle	Dodge-Caravan-LE-2
Manufacturer	Goodyear
Type	Steel-Belted
Mileage	7500

LE-2-LEFT-FRONT-TIRE

2.3.2.2 Rules

Production rules are another method of representing knowledge in the form of "If" conditions and "Then" actions. The conditions are commonly referred to as the premise or antecedents, and the actions as the consequent or conclusion [23]. Davis explains that the premise is always a conjunction of clauses, but each clause may also include nested disjunctions or conjunctions [20]. The consequent may contain one or more actions that are performed when the rule "fires." A necessary, but not sufficient, condition for rule "firing" is that all preconditions must be met.

When a rule actually fires after the premise is satisfied depends primarily on the inferencing strategy that is used by the knowledge-based system. For a forward-chaining strategy, Winston states:

> "To work forward with such rules, moving from condition-specifying <u>if</u> parts to action-specifying <u>then</u> parts, we use <u>forward-chaining</u>, and we speak of a <u>forward-chaining</u> <u>condition-action</u> <u>system</u> containing <u>condition-action</u> <u>rules</u> [22]."

With this strategy, rules are continually fired until all rules that can be fired have been fired. At that time, a KBES may have discovered several, one or no solutions.

The efficiency of the search for solutions can be improved through the use of the "OR" operator in the antecedent of a rule. Many rules have more than one precondition that must be satisfied before the rule fires. If there are alternatives to a precondition, the disjunctive "OR" operator can be used. When this operator is available in a KBES tool, the number of rules is reduced, which also reduces the resources needed to match rule antecedent conditions.

In addition to the forward-chaining strategy that is used in AIRPACS, rule sets and rule priority are also used to influence the order of rule firing [4, 20]. Rule sets also improve solution search efficiency by allowing the knowledge engineer to further reduce the resources required to match rule preconditions. They allow the knowledge engineer to group rules that solve a subgoal on the path to the ultimate goal [4]. For example, two logical rule sets for the rental company are engine and tire maintenance rule sets. In Goldworks II, only one rule set can be active at one time. Rule antecedent conditions are matched for a rule only if that rule belongs to the activated rule set. Since no resources are used to match rules not in the rule set, the KBES will find the solution much faster.

Another way of controlling rule firing in a KBES is to assign a priority to a rule. Goldworks II allows the knowledge engineer to assign a numerical value to a rule that ranges between 1000 and -1000 [4]. All rules with a priority of 1000 will be the first to fire while rules with a priority of -1000 will be the last to fire. Now that the rule control strategies used in AIRPACS are known, the next issue is how the inference engine finds descriptive data in object instances and then uses these data to match rule antecedent conditions.

Rules are satisfied by matching antecedent patterns with instance object patterns. The pattern matching capability of Goldworks II will be demonstrated by continuing with the rental company example problem. Lets assume the company's expert maintenance engineer knows that if fuel filters are replaced every 17,500 miles in all fuel-injected Mitsubishi engines, the fuel injectors will never have to be cleaned before the vehicle is sold. This knowledge could be represented as the rule shown in Figure 2-11.

All variables in Figure 2-11 are denoted by a question mark preceding the variable name. The empty closed parenthesis in the second line means all default values apply and that this rule is used in forward chaining and has a priority of 0. Once forward chaining is initiated, each precondition is <u>sequentially</u> matched [4]. If a variable is encountered, the system will bind all values to the variable that creates a pattern match.

FIGURE 2-11
FUEL FILTER RULE

```
(Define-Rule Replace-Fuel-Filter
  ()
  (Instance ?Engine-Name is Engine
      with Manufacturer Mitsubishi
      with Fuel-System Fuel-Injection
      with Part-of-Vehicle ?Vehicle
      with Mileage ?Total-Engine-Miles)
  (>= ?Total-Engine-Miles 17500)
   THEN
  (Print "Replace Fuel Filter On", ?Vehicle))
```

The first variable encountered is "?engine-name" so all instances of the class "engine" are matched. The next two preconditions of the rule state that the manufacturer must be Mitsubishi and the engine must have a fuel injection system. The search continues by binding the "?total-engine-miles" variable to the quantity of miles on each fuel injected Mitsubishi engine. Finally, if the value of this variable is greater than or equal to 17,500 miles, the next match identifies all those vehicles that should have their fuel filter replaced.

The rule in Figure 2-11 will fire once for every object instance that satisfies all the preconditions [4]. If the company has 100 Dodge Caravans with fuel injected Mitsubishi engines and 50 of those engines have more than 17,500 miles, then this rule will fire 50 times. The rental company example demonstrates how objects and rules complement each other. Effectively using each representation method enables the knowledge engineer to develop an overall strategy for a KBES that solves very difficult problems.

2.3.3 Blackboard Architecture

AIRPACS uses a Blackboard architecture to implement the pavement rehabilitation design process represented in this research. The concept of a Blackboard was first introduced in 1962 by Allen Newell [25]. This concept was tested and expanded until people began developing generic Blackboard tools which are extensions of expert system tools [23, 25]. This research uses Goldhill Computer's expert system tool to implement the Blackboard architecture for pavement design. Before the AIRPACS architecture is introduced in Chapter 4, it is important to appreciate the key characteristics of the Blackboard concept.

The two basic components of this concept include the Blackboard and knowledge sources (KS). Unlike the typical expert system which has only one knowledge-base, the Blackboard model has several knowledge-bases or knowledge sources. Each of these knowledge sources solves problems which contribute to the overall solution of a much larger problem. Since the work of one knowledge source may help another KS solve its task, the solution must be posted in one location where all KS have an equal opportunity to use the results [25]. This location is known as the Blackboard.

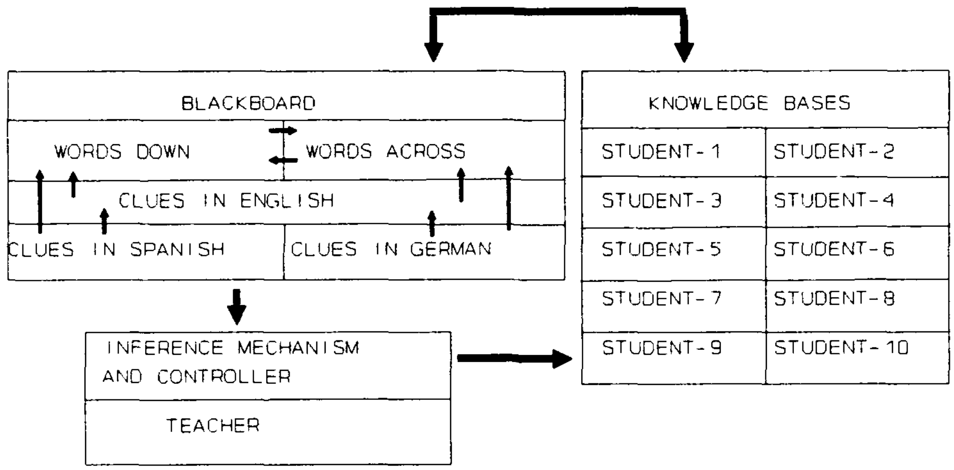
The KS communicate indirectly with each other through the Blackboard. There is no direct communication between the knowledge sources. Therefore, another key characteristic of a Blackboard architecture is each knowledge source works independently. Knowledge sources share task results, not task knowledge [25]. If the task results of a KS are needed by several knowledge sources, the results must be used in an orderly fashion.

A controller or scheduler on a Blackboard serves a role similar to a teacher in a classroom [25]. If ten students know the answer to a problem on the Blackboard, the teacher does not allow all ten students to rush to the board to solve the problem. Instead, the students are allowed to proceed to the board, one at a time, to solve a portion of the problem. The scheduler on the Blackboard controls KS access to the board in a similar manner. The following example reinforces the characteristics of the Blackboard architecture.

Lets assume a group of students in a classroom are going to solve a crossword puzzle that is drawn on a Blackboard. Although the clues to each of the English words are on the board, they are not written in English. Clues for the words "across" in the puzzle are in German while clues for words "down" in the puzzle are in Spanish. All 10 students in the class understand English, but only one understands Spanish while another understands German. Figure 2-12 shows how the crossword puzzle problem might be represented using a Blackboard architecture.

The teacher will allow either the student who understands German or the one who understands Spanish to go to the Blackboard first. Each of these students has the tasks of translating the clues to English and filling in the puzzle if they know any of the answers. As a student translates the clues, students who only understand English may be able to fill in more parts of the puzzle.

FIGURE 2-12
CROSSWORD PUZZLE ARCHITECTURE



However, the teacher will not let students go to the board until the translation of one language is complete. After the German or Spanish translation is complete, the teacher will let the remaining students go to the board, one at a time. As the puzzle is completed, some backtracking may be necessary to correct answers initially entered in the puzzle. Eventually the entire crossword puzzle will be completed correctly. In this example, each student may make a contribution to the overall goal, but students do not have all of the required knowledge to complete the puzzle by themselves.

The next chapter will present a detailed explanation of the pavement knowledge sources used in the Blackboard architecture of AIRPACS. A detailed discussion of the pavement knowledge formalized in this research sets the stage for knowledge representation and implementation in Chapter 4 using the Blackboard concepts that were introduced in this chapter.

CHAPTER 3

MODELLING THE AIRFIELD PAVEMENT REHABILITATION DESIGN PROCESS

This chapter describes the knowledge that was acquired to solve airfield rehabilitation design problems and constitutes the primary contribution of this thesis. Discussions focus on the knowledge and tools key players use to make their contribution in the rehabilitation design process. There may be many ways to arrive at a design solution, but this research strives to capture those methods that are fast and efficient. No matter how fast and efficient the method, many players use some analysis tools in their decision making. Successful use of these tools involves selecting the correct tool at the appropriate time and knowing how to use it efficiently. Before discussing problem-solving methods of individual players involved in the design process, the following sections will discuss the tools used in JPCP rehabilitation design.

3.1 DECISION-MAKING TOOLS

Although experts know how to use sophisticated tools, they also use simple tools to solve difficult problems. In fact, most pavement experts prefer to use simple tools to solve problems if the accuracy of the solution is not significantly compromised. Therefore, the author uses simple tools in the airport rehabilitation design process whenever possible. Some of the design tools presented in this section have not been used by consultants, the FAA, or the U.S. Air Force. The use of these design tools in the rehabilitation design procedures and the corresponding representation in AIRPACS also constitutes a new contribution to pavement engineering. Although no calls had to be made to an external computer program in this research, a KBES may have to use an external program if this is the only way an expert solves a problem. The following sections describe tools that were easily incorporated in AIRPACS to perform rehabilitation designs for a jointed plain concrete pavement (JPCP).

3.1.1 Pavement Condition Indices

Distresses visible on the surface of JPCP provide valuable input in the rehabilitation design process. An experienced pavement engineer can significantly narrow the list of feasible alternatives for a pavement by walking across the surface and noting all the distresses. After completing a visual inspection, the engineer is able to assign a qualitative rating to the pavement facility and identify several possible repairs. However, another experienced engineer may not agree with the rating or recommended repairs. In order to standardize survey methods and ratings, the pavement condition index (PCI) was developed.

In the mid 1970's, the PCI system was developed for the U.S. Air Force to help manage airfield pavements [26, 27]. The most interesting fact about the PCI development history is that heuristic knowledge was acquired and validated in a manner similar to that used in development of a traditional expert system. Many AIRPACS experts were also involved in the development of the PCI. This list of experts includes past and present Air Force MAJCOM pavement engineers and industry consultants. Although the PCI was originally developed for pavement network management, the success of the PCI has led many engineers to use PCI information in project design activities.

The PCI tool is one of the first used in the pavement rehabilitation process because it provides (1) a standard measure of the pavement condition in terms of structural integrity and operational condition, (2) an objective and rational method for identifying maintenance and repair needs and (3) an early warning system for identifying expensive repair projects [26]. The second objective is achieved by using qualitative ratings which are based on a PCI numerical value ranging from 0 to 100 as shown in Table 3-1. The method of determining the numerical value is simple enough to be calculated by hand, but most engineers use computer programs, such as PAVER [28, 29, 30], to speed up the evaluation process.

TABLE 3-1
PAVEMENT CONDITION INDEX RATINGS

PCI	100-85	85-70	70-55	55-40	40-25	25-10	10-0
RATING	EXCELLENT	VERY GOOD	GOOD	FAIR	POOR	VERY POOR	FAILED

The first step in completing a PCI survey is to divide the pavement facility into areas called pavement sections or features. A section is an area of a runway, taxiway or apron that has unique characteristics. Factors which make a section unique include pavement thickness, type of construction, pavement age and pavement use. The U.S. Air Force uses section designations to present pavement evaluation results and identify the scope of work for pavement projects. For this reason, AIRPACS uses the section as the basis for identifying feasible rehabilitation options for each section of a pavement facility.

Surveying an entire section is time consuming, so statistical sampling is used to reduce the amount of time required to survey large sections. The first step in the sampling process is to divide sections into sample units of approximately 20 slabs. Enough sample units must be sampled to be 95 percent confident that the mean PCI of all surveyed samples is within five points of the section PCI. During a survey, the technicians record pavement distress type, severity, and quantity, which is used to determine the deduct value for each distress. The deduct curves that exist for each distress and severity are a function of the distress density and were constructed using the experience and judgement of several cooperating experts.

The shape of a deduct curve and the magnitude of a deduct value reflect the experts' concern for a particular distress type, severity and quantity. Table 3-2 lists all JPCP distresses considered in determining the PCI and the maximum deducts for each severity level [31, 32]. The maximum deducts shown in the table are an indication of how strongly pavement experts feel a distress adversely impacts pavement performance. Table 3-2 also shows that the sum of all deducts for a section sample unit could easily exceed 100. If this deduct total were then subtracted from 100, the PCI would be less than zero. This problem is corrected with the use of more heuristic curves.

The deduct correction curves reduce the sum of the deducts for those section samples that have distresses with deduct values greater than five points. The amount of the reduction depends on the number of deducts that are greater than five points. After the modified deduct total is determined, this revised total is subtracted from 100 to give the sample unit PCI. Although the procedure for determining the PCI value is straightforward, the PCI variance among sample units could be quite high if the technicians do not correctly identify distress types and severities.

Survey manuals [31, 32] help the technician identify the type of distress and select the correct severity level so that the PCI can be objectively determined. These manuals describe each distress by severity and have photographs of all distress severity levels. With some training, an inexperienced technician can perform a condition survey and produce statistically valid results. The success of the PCI survey method is one reason that this empirically based tool has been included in AIRPACS [33].

TABLE 3-2
MAXIMUM JPCP DISTRESS DEDUCTS

DISTRESS	HIGH SEVERITY	MEDIUM SEVERITY	LOW SEVERITY
Blowup	(1)	100	100
Shattered Slab *	100	83	58
Corner Break *	92	73	42
Settlement	90	57	37
Durability Cracks	88	53	18
Large Patch	88	49	22
Scaling	87	53	17
Long/Trans/Diag Cracking *	84	57	22
Joint Spalling	52	37	14
Corner Spalling	46	28	19
Pumping (2)		52	
Small Patch	41	22	10
Popouts (2)		22	
Shrinkage Cracks (2)		14	
Joint Seal Damage (3)	12	7	2

NOTES
(1) No high severity level for this distress
(2) No severity level but deduct depends on distress density
(3) Severity levels but deduct does not depend on distress density
(4) "*" indicates those distresses used to compute the structural condition index (SCI)
(5) Shaded areas indicate those distresses and severity levels used to compute the FOD condition index (FCI)

Two of the experts who participated in the original development of the PCI, Darter and Shahin, realized that the information gathered in the PCI survey could be used to quantify the structural integrity of the pavement [34]. The procedure for computing the PCI value is also used to compute the structural condition index (SCI). Only those distresses with an asterisk in Table 3-2 are used to calculate the SCI. Although fewer distresses are used to calculate the SCI, the magnitude of the distress deducts can still lead to a pavement with a "failed" SCI rating. Thus, the ratings used for the PCI can also be used to assign a SCI rating to a pavement section.

Further inspection of the data collected during a PCI survey shows that there is another airfield use for this data. One of the objectives of the PCI is to provide a standard measure of the pavement condition in terms of operational condition [26]. Engine FOD susceptibility is an operational concern which can be addressed using PCI data. This research proposes the use of a FOD condition index (FCI) to provide additional input in the design process. The FCI is calculated using deducts for those distress and severity levels shaded in Table 3-2. This index allows one to assess the FOD potential by comparing FOD generation with aircraft engine susceptibility to FOD.

The PCI, SCI and FCI tools are effective planning tools since they may be used to quickly reduce the number of feasible rehabilitation options. Once the number of options is reduced, additional tools must be used to study the feasible options in more detail. The tools needed at this point in the design process are absent from PAVER, a pavement management tool which also uses PCI data to help users make key repair decisions. The absence of additional tools and the knowledge of how to use these tools are the reasons that PAVER cannot provide guidance through all phases of the design process.

PAVER is a pavement management tool that was developed under the guidance of Shahin [3, 27, 35, 36, 37, 38, 39, 40]. During the development of PAVER, many years of pavement experience were successfully captured and used to develop the maintenance guidelines shown in Table 3-3 [37], which are also represented in AIRPACS. Table 3-3 identifies several repair choices for each of the distresses in Table 3-2. The repairs are used for preventive maintenance or to correct locally distressed areas. More extensive repairs such as structural overlays or reconstruction must be considered if PCI distresses that are load-related occur systematically over the entire section or pavement facility.

TABLE 3-3 [37]
M&R METHODS FOR AIRFIELD JPCP

DISTRESS TYPE	METHOD					
	Do Nothing	Crack Sealing	Joint Sealing	Partial-Depth Repair	Full-Depth Repair	Replace Slabs
Blow-Up				L M	M	M
Corner Break	L	L M H			M H	
L/T/Diag Cracking	L	L M H		H	H	H
"D" Cracking	L	L	L	M H	M H	H
Joint Seal Damage	L		M H			
Small Patch	L	M		M H	H	
Large Patch	L	M		M H	H	H
Popouts	A					
Pumping (1)		A	A			
Crazing/Scaling	L			M H		H (3)
Faulting (2)	L					H
Shattered Slab		L M H				M H
Shrinkage Cracks						
Joint Spalling	L		L M	L M H	M H(4)	M H(4)
Corner Spalling	L		L M	M H		

NOTES:
(1) Undersealing is an acceptable M&R method.
(2) Slab jacking and slab grinding are acceptable M&R methods for medium and high severity level distresses.
(3) Replace only when surface is unacceptable
(4) If caused by keyway failure, provide load transfer
(5) L, M & H are low, medium and high severity level distresses
(6) "A" means distress has no severity level

The EVALSUM module was added to PAVER to help a user select a preliminary set of feasible maintenance and repair (M&R) alternatives from a list of all possible rehabilitation alternatives [39]. However, PAVER does not have enough knowledge to critically evaluate the list and further screen rehabilitation alternatives. To accomplish this objective, deep pavement knowledge [41] has been captured in AIRPACS to use the following tools and move on to subsequent steps in the rehabilitation design process.

3.1.2 JPCP Stress Calculations

Flexural stresses induced in a slab by an aircraft have a major effect on slab cracking. In the past, many agencies have made very approximate assumptions in the calculation of flexural stresses in a JPCP under aircraft loads. Agencies often assume that load transfer across joints reduces slab edge stress by 25 percent, regardless of the joint type. This assumption should no longer be used since it may produce inaccurate results. Foxworthy, Ioannides and Korovesis have developed models that describe the behavior of concrete joints [10, 42, 43]. One of the key concepts used in each of these models is the radius of relative stiffness, ℓ (Equation 3.1) [44].

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1-\mu^2)k}} \qquad \text{EQN 3.1}$$

ℓ = radius of relative stiffness (in)
E = modulus of elasticity of the concrete (psi)
h = thickness of the concrete (in)
μ = Poisson's ratio of the PCC slab
k = modulus of subgrade reaction (psi/in)

Westergaard introduced the radius of relative stiffness in 1926 [44]. This parameter relates slab stiffness to the stiffness of the foundation. Slab stiffness is defined in terms of the concrete elasticity, thickness, and Poisson's ratio while the foundation stiffness is described by the modulus of subgrade reaction, "k," which is analogous to a spring constant. This value is not an intrinsic material property but depends on the rate of load application, vertical stress, types of layers beneath the layer being tested, JPC layer thickness and the modulus of elasticity of the JPC layer. Static modulus values are determined by dividing the load applied to a 30-inch-diameter test plate (10 psi) by the resulting plate deflection. Most "k" values are between 50 and 400 with a typical value being 200 psi/in.

The radius of relative stiffness appears in Westergaard's original stress and deflection equations for concrete [44]. Westergaard's stress and deflection equations were developed for corner, interior and edge loading conditions. Each of these equations is for a load with a radius, "a". Ioannides et al. used the finite element program ILLI-SLAB [45] to review and identify the correct forms of these equations [46, 47]. AIRPACS uses the edge stress equation (Equation 3.2) [46, 47] since this is the critical loading location [10] for most aircraft traffic. Like all the original Westergaard equations, Equation 3.2 is limited in applicability to a single load, i.e., not for larger aircraft with multiple-wheel gear.

$$\sigma = \frac{3(1+\mu)P}{\pi(3+\mu)h^2}\left[\ln\frac{Eh^3}{100ka^4}+1.84-\frac{4\mu}{3}+\frac{1-\mu}{2}+1.18(1+2\mu)(a/\ell)\right] \qquad \text{EQN 3.2}$$

σ = free edge stress (psi)
E = modulus of elasticity of the concrete (psi)
h = thickness of the concrete (in)
μ = Poisson's ratio of the pavement
k = modulus of subgrade reaction (psi/in)
a = load radius (in)
ℓ = radius of relative stiffness (in)
P = load (lbs)

3.1.3 Aircraft Equivalent Single Wheel Radius (ESWR)

Because of this limiting load condition, the equivalent single wheel load (ESWL) concept was introduced to allow the engineer to apply Westergaard's equations to multiple-wheel gear loads. Yoder and Witczak [48] define the ESWL as follows:

"An equivalent single-wheel load (ESWL) is defined as the load on a single tire that will cause an equal magnitude of a preselected parameter (stress, strain, deflection, or distress) at a given location within a specific pavement system to that resulting from a multiple-wheel load at the same location within the pavement structure."

An alternative approach to the ESWL concept is the equivalent single-axle radius (ESAR) concept, first introduced by Ioannides, et al [49, 50]. The definition of ESAR is identical to the definition of ESWL given above, except that the words "load on" are replaced by "radius of." Ioannides introduced ESAR to replace the ESAL (equivalent single axle load) concept which is associated with highway traffic analysis and design.

A natural extension of ESAR for airfield analysis and design would be an equivalent single-wheel radius (ESWR), since ESWL is the most common acronym associated with airfield analysis and design. Since the number and spacing of tires on the main gear of large aircraft vary significantly, the ESWR concept makes stress and deflection analysis much easier. For very large aircraft, as many as six tires on a gear can be converted to a single equivalent radius, allowing the designer to use Equation 3.2 to calculate the free edge stress in a slab. The procedure used in this research to determine the ESWR for an aircraft is summarized in Figure 3-1.

FIGURE 3-1
AIRCRAFT ESWR DETERMINATION

STEP 1: Use the H51 computer program to determine the flexural stress for the transverse edge loading condition. Edge stresses are determined for pavement structures with ℓ values ranging from 12 to 130.

STEP 2: Solve for "a" in Eqn 3.2 using the total gear load and the H51-determined edge stresses. This results in a unique ESWR for edge stresses in structures with different ℓ values.

STEP 3: Use multiple regression to determine equations for ESWR as a function of ℓ.

STEP 4: Validate the regression equations using a new set of ℓ values. Compare stresses using the H51 program, ESWR equations and Eqn 3.2 and the U.S. Army Corps of Engineers' regression equations for aircraft.

Computer runs were used to validate the aircraft ESWR equations currently in AIRPACS. Since the free edge stresses from the H51 program [51] are usually within three percent of the free edge stresses determined from a finite element program, such as ILLI-SLAB, the H51 results are the basis of comparison. The results in Appendix B show that use of the ESWR concept proposed by Ioannides leads to very accurate results, and in most cases, produces better results than the Corp of Engineers' equations used in their rigid airfield design program (RAD807) [52]. In addition, some of the Corp's equations apply for the longitudinal edge loading condition versus the transverse edge loading condition, which is always used in AIRPACS.

3.1.4 Joint Load Transfer Efficiency

Once the free edge stress is known, another tool is used to estimate edge stress reduction due to load transfer across the joints. Ioannides and Korovesis have developed a model (Figure 3-2) [50] that expresses the relationship between deflection load transfer efficiency (DLTE) and stress load transfer efficiency (SLTE). DLTE and SLTE are defined in Equations 3.3 and 3.4, respectively.

DLTE $= \delta_u/\delta_l * 100\%$ EQN 3.3

δ_u = deflection of adjacent unloaded slab
δ_l = deflection of loaded slab

SLTE $= \sigma_u/\sigma_l * 100\%$ EQN 3.4

σ_u = edge stress of adjacent unloaded slab
σ_l = edge stress of loaded sla

Figure 3-2 shows that the DLTE vs. SLTE relationship depends on the load size ratio, a/ℓ [50]. Since the slab length (L) over ℓ (L/ℓ) and slab width (W) over ℓ (W/ℓ) ratio assumptions of Figure 3-2 represent typical ratios in the field, the curves in this figure are used to determine slab edge stresses, once free edge stress and the DLTE are known. The DLTE is usually determined using a Falling Weight Deflectometer (FWD) during a pavement evaluation, but if no evaluation results are available, the DLTE must be estimated. Darter, et al., reported the range of DLTE values shown in Table 3-4 for the various types of joints in concrete pavements [6].

FIGURE 3-2 [50]
SLTE vs. DLTE FOR A SYMMETRIC EDGE LOAD

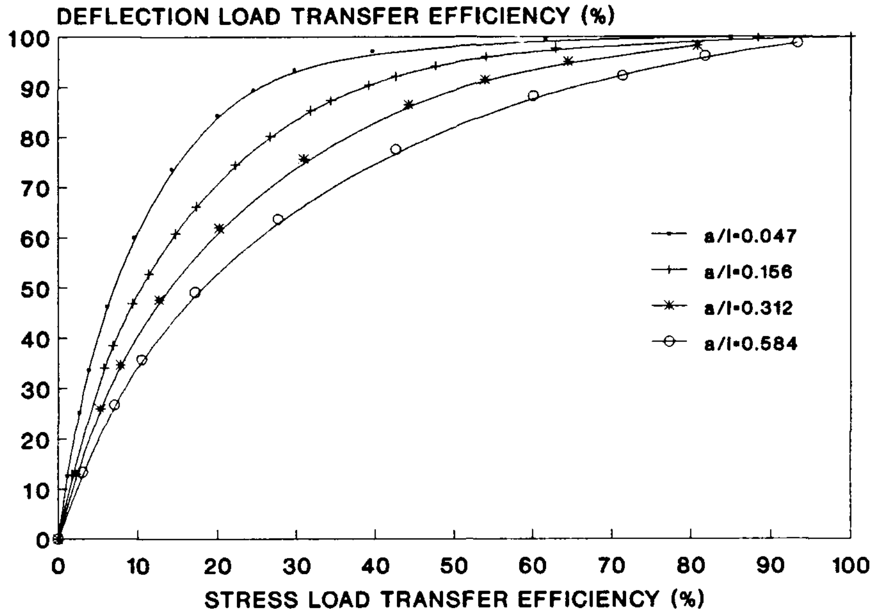


TABLE 3-4 [6]
TYPICAL DLTE VALUES

JOINT TYPE	BASE TYPE	DLTE (Percent)
Weakened Plane	Granular	40 to 60
Weakened Plane	Stabilized	50 to 70
Keyway	Granular	50 to 70
Keyway	Stabilized	60 to 70
Doweled	Any Type	70 to 90

The curves in Figure 3-2 show that the SLTE is not linearly proportional to DLTE, but decreases very rapidly once the DLTE falls below 80 percent. To improve the accuracy of estimating DLTE when evaluation results are unavailable, Foxworthy's DLTE model [10] is used to estimate the DLTE for a geographic region of the United States. Foxworthy suggested that the typical DLTE vs. temperature relationship could be expressed in the form of an S-shaped curve [10]. When the pavement section has sawed or keyed joints, AIRPACS uses Equation 3.5 [10] and a shift factor of 50 degrees fahrenheit (283 degrees kelvin) to estimate load transfer across the slab joint.

$$DLTE = 0.25 + 0.75e^{-(SF/AT)^{40.0}} \qquad \text{EQN 3.5}$$

SF = Shift Factor (Expressed in Degrees Kelvin)
AT = Air Temperature (Expressed in Degrees Kelvin)

If a pavement section does not have sawed or keyed joints and no falling weight deflectometer (FWD) evaluation results are available, AIRPACS uses a DLTE value within the range of values specified in Table 3-4 for a doweled joint. Ioannides and Korovesis have developed a relationship between DLTE and a dimensionless joint stiffness factor for a doweled joint, but a variable cF this factor, the modulus of dowel support "K," cannot be reasonably estimated at this time [53]. Therefore, a mean DLTE value of 85 percent for doweled joints is used in AIRPACS when pavement evaluation results are not available. Once the free edge stress and stress load transfer efficiency across a joint are known, the edge stress along the transverse joint may be computed. At this point the engineer needs a tool which uses edge stresses to estimate past and future concrete fatigue damage so the structural life of the pavement can be assessed.

3.1.5 Concrete Pavement Fatigue Damage

One of the most debated and least understood issues in the rehabilitation design process is pavement fatigue damage, which depends primarily on the types of aircraft that use the airport and the average annual passes of each aircraft. At the present time, the best method of estimating fatigue damage is to use statistical regression equations which predict the allowable number of passes of an aircraft [10]. The equations are usually based on the Corps of Engineers' full-scale test sections. (Reference 21 contains a list of the test section reports from these full scale tests.)

Engineers often disagree on what constitutes JPCP failure. For structures such as bridges or dams, structural failure is obvious, but this is not the case for pavements. The Corps of Engineers defines pavement structural failure as the point in the pavement's life when 50 percent of the slabs have a visible surface crack [10]. However, Rollings suggests using the SCI to define failure since many pavements may have an operationally acceptable surface when more than 50 percent of the slabs are cracked [54]. Since Darter has obtained good results using Equation 3.6, which is based on the Corps of Engineers' full-scale tests and pavement failure definition, AIRPACS uses this model to estimate allowable aircraft coverages [55].

$$Log_{10}COV = 2.13\left(\frac{Mr}{\sigma}\right)^{1.2} \qquad \text{EQN 3.6}$$

COV = Number of coverages to 50 percent slab cracking
Mr = Third-point modulus of rupture calculated from dynamic modulus of elasticity from FWD (psi)
σ = Critical stress in the slab using appropriate joint load transfer (psi)

R Squared = 0.60 Standard Error = 0.58 n = 51

Equation 3.6 enables the engineer to estimate the allowable number of load repetitions for one stress ratio. But an airport pavement engineer must consider several aircraft which all create different magnitudes of flexural stress in the slab. For JPCP pavement sections, AIRPACS uses Equation 3.6 as a tool to compute the allowable coverages for each aircraft. This equation is used to determine the number of coverages that one type of aircraft can make before failure occurs, but this number must be reduced if several types of aircraft will use a pavement facility. Miner's hypothesis (Equation 3.7) [56] can be used to estimate past and future fatigue damage for all aircraft when the number of past and future coverages for each aircraft is less than the allowable number of coverages.

$$1.0 \approx \sum_{j=0}^{air_p} \frac{COV_j}{COV_a} + \sum_{k=0}^{air_f} \frac{COV_k}{COV_a} \qquad \text{EQN 3.7}$$

air_p = number of aircraft types that used the pavement in the past
air_f = number of aircraft types that will use the pavement in the future
COV_j = actual number of past coverages for aircraft "j"
COV_k = estimated number of future coverages for aircraft "k"
COV_a = number of allowable coverages before 50 percent of the slabs crack

Since pass-to-coverage ratios depend on the location of an aircraft's gear on the pavement with respect to the location under consideration, several locations must be checked to determine the critical location for mixed aircraft traffic. AIRPACS estimates the maximum amount of damage each aircraft contributes and then designates the critical aircraft as the aircraft whose main gear will damage the pavement the most in the future. Next, AIRPACS compares the critical aircraft's gear location to the gear location of all remaining aircraft.

Since gear location can be measured relative to the facility centerline, aircraft gear spacing differences are used to modify the P/C ratios for all non-critical aircraft. The modified P/C ratio can then be used to modify the fatigue damage contribution of each aircraft relative to the main gear location of the critical aircraft. Assuming the aircraft wander follows a normal distribution, the maximum ordinate, C_{xc}, is defined in Equation 3.8 [8]. C_{xc} values for non-critical aircraft are revised by computing z as shown in Equation 3.9.

$$C_{xc} = \frac{f(z)}{S_x} = \frac{e^{-0.5z^2}}{\sqrt{2\pi}} * \frac{1}{S_x} = \frac{1}{(\frac{P}{C})(W_t)} \qquad \text{EQN 3.8}$$

$$z = (X-\mu)/S_x \qquad \text{EQN 3.9}$$

= standard normal deviate (x-axis)

X = 1/2 * [(Critical Aircraft Main Gear Spacing) - (Gear Spacing of Non-critical Aircraft)]

μ = population mean = 0

f(z) = the probability density of a standardized random variable (y-axis)
x = a variable of the actual aircraft distribution curve (x-axis)
C_{xc} = maximum ordinate of actual aircraft distribution curve
S_x = standard deviation of the actual aircraft distribution which is is assumed to be 60 inches for runways and 30 inches for taxiways
W_t = tire width
P/C = pass-to-coverage ratio

To simplify the computation of a revised C_{xc}, the ratio of the unadjusted C_{xc} to the adjusted C_{xc} is approximated by computing this ratio as if the aircraft's main gear had only one tire. Next, the ratio is used to adjust the damage contribution by a non-critical aircraft using equations 3.7, 3.8 and 3.9.

Once the maximum fatigue damage is determined for each aircraft, only three pieces of input data are required to compute fatigue damage at the critical aircraft's gear location. The required data include the type of facility, the critical aircraft's main gear spacing and the non-critical aircraft's main gear spacing. This method of revising the maximum Miner's damage for all non-critical aircraft to compute the cumulative damage at the critical aircraft's main gear location simplifies fatigue damage calculations.

After the estimated future damage for each non-critical aircraft is adjusted, past fatigue damage is added as described by Equation 3.7. This model allows AIRPACS to compute total Miner's damage at the critical aircraft's main gear location on the pavement. The total fatigue damage must be between 0.90 and 1.05.

,.1.6 Structural Overlay Thickness Determination

AIRPACS uses the tools described up to this point to determine a single layer thickness that will be used for a reconstructed JPCP, an unbonded JPCP overlay, a bonded JPCP overlay or an asphalt overlay. The single layer thickness that AIRPACS computes for reconstruction or an asphalt overlay does not include past Miner's damage. However, past Miner's damage is included in the single layer thickness calculations for a JPCP bonded overlay. Section 3.2.4 explains when past Miner's damage is used to compute the single layer thickness for a JPCP unbonded overlay.

For reconstruction, the single layer thickness is the new reconstruction thickness, but additional work is required to determine overlay thicknesses. This work can be accomplished by using Equations 3.10 and 3.11 which are empirical overlay equations that were developed by the Corps of Engineers. Although these equations are empirical, they have been calibrated to reflect overlay performance in the field [14]. Equations 3.10 and 3.11 have been used in various forms by the FAA and the U.S. Air Force.

The general forms of the overlay equations for PCC pavements are shown in equations 3.10 and 3.11 [6, 7, 14, 15]. The limitations and history of these PCC and asphalt overlay equations are described by Darter and Smith [14]. The C_r, C_b and F factors shown in equations 3.10 and 3.11 are subjectively determined if the engineer uses FAA or U.S. Air Force design procedures [7, 15]. As a result, the variance of overlay thicknesses computed using these equations may be quite high. The rehabilitation design decision-maker module discussed in section 3.2.4

presents procedures that Shahin and Darter have introduced for consistent selection of values for these condition factors. In addition, section 3.2.4 presents a new method of determining the JPCP unbonded overlay thickness.

$$h_{ol} = \sqrt[n]{(h_{np}{}^{n} - C_r h_{ep}{}^{n})} \qquad \text{EQN 3.10}$$

h_{ol} = thickness of the PCC overlay
h_{np} = pavement reconstruction thickness
h_{ep} = thickness of the existing pavement
C_r = condition factor of the existing pavement with a value that ranges from 0.35 to 1.0
n = 1.0, 1.4 and 2.0 for bonded, partially bonded and unbonded overlays, respectively

$$t = 2.5(Fh_{ol} - C_b h_{ep}) \qquad \text{EQN 3.11}$$

t = thickness of the AC overlay
h_{np} = pavement reconstruction thickness
h_{ep} = thickness of the existing pavement
F = factor which controls the degree of cracking in the existing pavement
C_b = condition factor of the existing pavement with a value that ranges from 0.50 to 1.0

3.1.7 JPCP Joint Spacing

Once the thickness of the reconstructed JPCP or JPCP overlays is determined, another tool must be used to select a reasonable joint spacing. Joint spacing must be carefully selected since the spacing has a significant effect on the magnitude of curling and warping stresses in a JPCP. There are times in a day when aircraft load induced stresses and curling stresses may be additive, leading to stresses that are two to three times the load stress predicted by Equation 3.2 [49, 58, 59, 60]. Since it is very difficult to directly incorporate curling and warping stresses in a fatigue analysis, many heuristics have been used to provide guidelines for joint spacing for JPC pavements.

All existing airfield design manuals include tables with joint spacing recommendations based on the JPCP thickness [6, 7, 15]. Many engineers use the heuristic that joint spacing (in feet) should not be more than 1.75 to 2.0 times the slab thickness (in inches) [59, 60]. Recent finite element analysis work and investigation of pavement performance in the field have shown that this heuristic does not consider all pertinent parameters in joint spacing selection.

Since ℓ is a function of the parameters h, E, and k, researchers and consultants are beginning to make joint spacing recommendations based on the ℓ value of a JPCP section. A joint spacing of 4ℓ has been suggested by Ioannides and Salsilli based on ILLI-SLAB finite element runs [59]. Smith et al. studied the performance of 53 JPCP highway sections across the United States which had a wide range of joint spacings [60]. Based on pavement performance, they recommended a joint spacing of 5ℓ for a JPCP with a stabilized base course and 6ℓ for a JPCP with an unbound base course.

One reason for using two joint spacing recommendations is that the "k" value of a stabilized material beneath the JPC layer is frequently higher than the "k" value for an unbound material. A stiffer supporting medium increases the curling stresses in the PCC layer [48]. In addition, the coefficient of friction is normally much higher for a stabilized material than it is for an unbound material [61]. All other factors being equal, this will result in higher shrinkage- and temperature-induced tensile stresses in the slab.

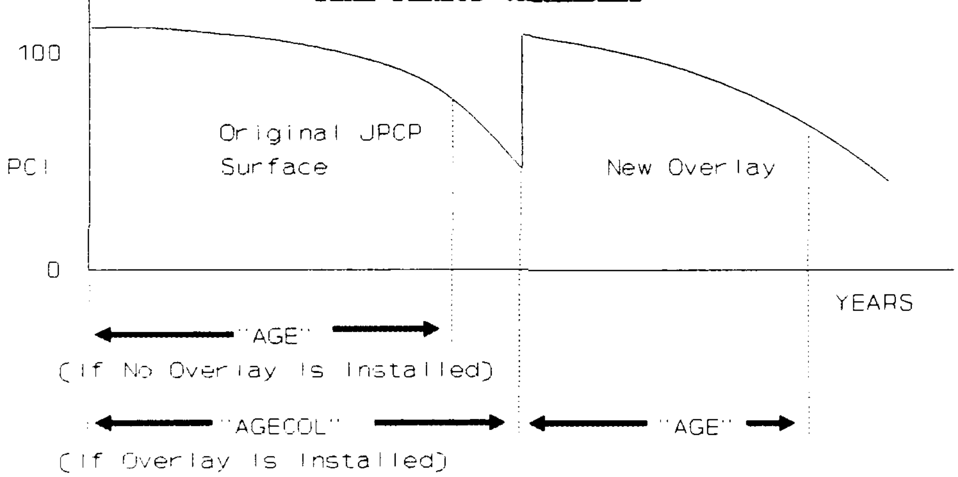
After a review of U.S. Air Force airfield JPCP sections and the recommendations made for highway pavements, it was decided to use more conservative joint spacings for these JPCP sections. The PCC layer thicknesses of airfield pavement facilities may be greater than 20 inches which is much larger than the thicknesses found in highway JPC pavements. Furthermore, it is common practice to tie the three outer slabs of a pavement facility to each other [7, 15]. For these reasons, the shrinkage- and temperature-induced tensile stresses in the slab may be higher in airport pavements than they are in a highway JPCP. Until further research is conducted on this topic, AIRPACS will recommend joint spacings of 4ℓ and 5ℓ for bound and unbound base courses, respectively.

The tools introduced to this point give the engineer the capability to select JPCP structural thicknesses and joint spacings, but additional tools are needed to predict how the climate affects pavement performance. Since Equation 3.6 does not account for environmental effects, a KBES should use climatic information to predict pavement performance. Performance prediction tools should not only predict how overlays or new pavements will perform, but how localized repairs will alter the current pavement deterioration rate. If climatic and aircraft traffic are both considered in a knowledge-base, KBES users will be able to make more informed decisions when they select an alternative.

3.1.8 PCI Prediction Models

During the development of the PCI and PAVER, several performance prediction models were constructed using data from 12 U.S. Air Force bases that are located in various climatic regions of the United States. Models were developed to predict future PCI values, percent of slabs with corner breaks and percent cracked slabs [3]. Of the three models, the only model that provides reliable results is the PCI model.

FIGURE 3-3 [3]
TIME PERIOD VARIABLES



The PCI model is used in AIRPACS to construct a PCI versus time curve for feasible rehabilitation alternatives. There are many different ways to measure the benefit or performance of an alternative, which is used to select an optimal solution at the project or network level [16]. In AIRPACS, performance is measured in terms of the PCI versus time curve, as illustrated in Figure 3-3. The area under the curve describes the performance of a specific alternative. Equations 3.12, 3.13 and 3.14 [3] are used to predict the PCI for JPCP pavements for each year throughout the design life.

$$PCI = 99.5364 - (2.6833)(AGE^{0.5586})(LDAMAGE^{0.6}) - (0.0001757)(AGE^{0.5})(FATAGE^{0.74987}) - (0.0021893)(AGE)(AAPREC^{1.2188}) - (0.02987)(AGE^{1.7366})(FTC) - (0.03191)\left(\frac{AGE^{5} * AGECOL^{0.76544} * LDAMCOL}{THICK^{1.6035}}\right) \qquad \text{EQN 3.12}$$

R Squared = 0.74 Standard Error = 8.12 n = 162

PCI	= Pavement Condition Index
AGE	= Time (years since original construction or, if overlaid, time since overlay construction)
AAPREC	= Average annual precipitation (inches)
FTC	= discrete variable
	= 1 if the number of freeze-thaw cycles in a PCC pavement at a 2-inch depth is greater than or equal to 10
	= 0 if number of freeze-thaw cycles in a PCC pavement at a 2-inch depth is less than 10, or if the existing pavement is an asphalt overlay
THICK	= The most recent overlay thickness (for overlaid pavements only)
AGECOL	= Age of previous surface layer before being overlaid (Fig 3-3).
DAMCOL	= Damage done to the pavement structure during the time period "AGECOL." Calculated using "DAMAGE" procedure.
LDAMCOL	= LOG_{10}(DAMCOL + 10)
LDAMAGE	= LOG_{10}(DAMAGE + 10)

$$FATAGE = \sum_{j=1}^{a} (0.75)\left(\frac{\sigma_{ej}}{MR}\right)(n_j)(AGE) \qquad \text{EQN 3.13}$$

a	= number of different aircraft using the section
σ_{ej}	= edge stress caused by aircraft "j" as computed by the H51 computer program (psi)
Mr	= modulus of rupture of concrete (psi)
n_j	= Total number of passes per year (not coverages of aircraft "j")

$$DAMAGE = \sum_{j=1}^{a} \left(\frac{n_j}{N_j}\right)(AGE) \qquad \text{EQN 3.14}$$

N_j	= number of repetitions of aircraft "j" to cause failure of the JPCP

By using Equation 3.12 to compute the annual PCI and a "PCI vs. time" curve, AIRPACS includes the effect of climate on pavement performance. This equation accounts for freeze-thaw cycles and precipitation, two environmental factors which can significantly impact pavement performance. After the performance for each feasible alternative is determined, the KBES user will also want a traditional economic analysis to complete the design process and provide additional guidance for selecting a rehabilitation method.

3.1.9 Economic Analysis

Before the equivalent uniform annual cost (EUAC) of each feasible alternative can be computed, the present worth of each alternative must be calculated as shown in Equation 3.15 [57]. The present worth includes initial construction costs, future maintenance costs and the salvage value of the pavement at the end of its design life. Once the present worth of expenditures and salvage values is known, the EUAC can be computed using Equation 3.16 [57], allowing the KBES to help the user make a better selection among the list of designed alternatives.

$$PW = \sum_{j=1}^{NEXP} \frac{EXP_j}{(1+i)^n} \qquad \text{EQN 3.15}$$

PW = Present worth
n = Number of years alternative is discounted over
NEXP = Number of expenditures and salvage values
EXP = Expenditure or salvage value
i = Discount rate

$$EUAC = PW * \frac{i(1+i)^n}{(1+i)^n - 1} \qquad \text{EQN 3.16}$$

EUAC = Equivalent uniform annual cost

The preceding discussion describes the tools that are needed to complete a successful and comprehensive design, but a tool's potential is not realized until an experienced player in the design process skillfully uses the tool to solve difficult problems. The next sections describe what, when and how each tool is used by each player in the design process to complete their work tasks. As the next section illustrates, some players are very tool dependent while others can solve their tasks without any tools.

3.2 REHABILITATION DESIGN DECISION-MAKERS

A majority of the knowledge acquired during this research focuses on the planner and designer since a majority of the work accomplished in the design process is performed by these players. This in no way diminishes the value of other players involved in the design process since all player input is necessary for a successful design. The first player in the design process is the planner who uses all available information about an airport to make decisions about the feasibility of each potential rehabilitation alternative.

3.2.1 Planner

The primary objective of the planner is to review all available pavement, climate and aircraft data and then select feasible rehabilitation alternatives for one or more sections of a pavement facility. Much M&R expertise was captured during the development of a pavement management program for the U.S. Air Force between 1974 and 1983. The planning knowledge captured in AIRPACS builds on the planning knowledge in PAVER, a pavement management computer program.

Three repair categories that were identified during the development of PAVER include ROUTINE, MAJOR and OVERALL repairs. ROUTINE M&R consists of preventive or localized M&R [37]. MAJOR M&R is an extensive form of localized M&R which includes partial-depth or full-depth repair, slab replacement, slab undersealing and slab grinding. Finally, the scope of OVERALL M&R work includes the entire pavement and usually improves the load-carrying capacity of the pavement. This category of repair includes overlays, recycling and reconstruction.

The planning knowledge in AIRPACS builds on the knowledge already in PAVER, especially in the OVERALL repair category. For example, PAVER identifies Portland Cement Concrete (PCC) as an overlay alternative while AIRPACS uses additional knowledge to determine if bonded or unbonded JPCP overlays are feasible [39]. Most of the planning knowledge acquired for AIRPACS was obtained from experts within the Department of Defense (DOD) and Darter.

3.2.1.1 Planner Knowledge Acquisition

The knowledge acquired during this research should be not be viewed as a typical "first" interview in the knowledge acquisition process [62, 63]. Between 1974 and 1983, a significant amount of knowledge was captured during the development of the PCI and used in the various pavement management modules present in PAVER [40]. The interviews conducted during this research took advantage of the pavement terminology developed during the 1974-1983 time period. Since that time, PAVER has been tested in the field, and various strengths and weaknesses have been identified.

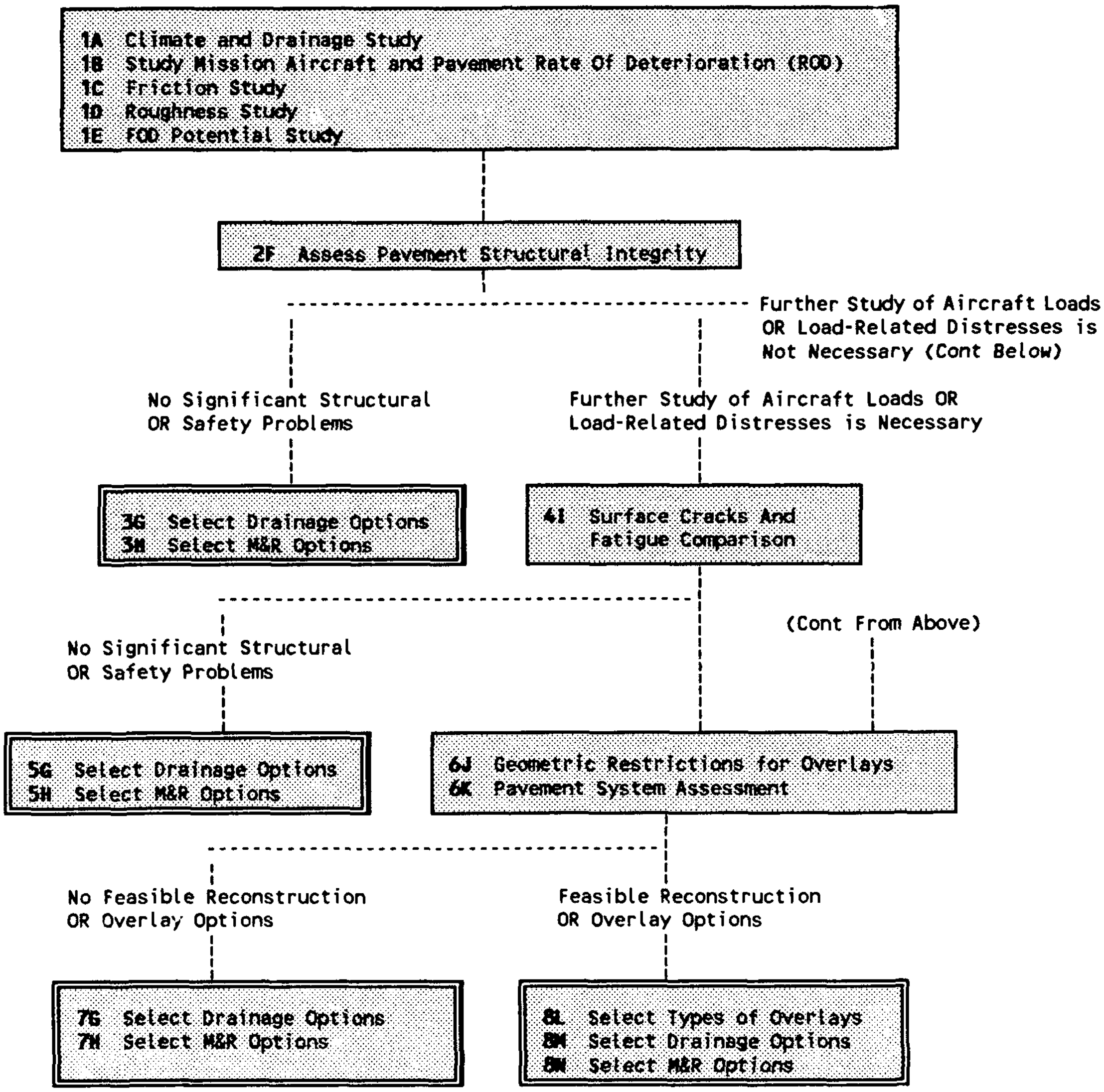
For all engineers who were interviewed in knowledge acquisition sessions, the PCI data that was included in case scenarios was invaluable. Pictures were not part of the data, so pavement experts had to use PCI distress, severity and quantity data to visualize the JPCP surface condition. The following sections reflect the planning process and data that most experts used as they reviewed each of the problems scenarios and identified feasible rehabilitation alternatives.

3.2.1.2 General Assessment of JPCP Sections

The first step in the planning process is to review all aspects of the airport environment which may affect pavement performance. Engineers will use general knowledge about the climate, soil topography, aircraft characteristics, traffic and safety issues to quickly focus on issues that may help them select feasible rehabilitation alternatives. The decision tree shown in Figure 3-4 provides an overview of the entire rehabilitation planning process. The first node in Figure 3-4 includes all the actions associated with the initial assessment of an airport.

In a classical decision tree, such as the tree shown in Figure 3-4, nodes and arcs form the paths to one or more conclusions. Since decision trees can be

FIGURE 3-4
PLANNING PROCESS DECISION TREE



NOTES:
(1) Each shaded box is a node in the decision tree.
(2) Nodes are numerically identified while actions are noted by letters (i.e. Actions "L", "M" and "N" must be completed for node 8).
(3) "Non-boxed" text groups in Decision Tree 1 are the path discriminators in the decision tree.

quite large, key decision tree information has been summarized using a decision tree summary (DTS). Although a DTS does not show the paths to each conclusion, it allows the reader to quickly review the factors and the path discriminators which lead to a conclusion. For those readers who want to know how each conclusion is reached, decision tree node, arc and path information has been added to the decision tree summaries in Appendix E.

3.2.1.2.1 <u>Climate And Drainage Study</u>

One of the first actions in the planner's initial assessment is to identify key characteristics of the airport climate. Moisture and temperature characteristics of a region are considered early in the planning process since climate may have a significant affect on pavement performance. DTS 3-I-1A shows the decision tree nodes and path discriminators used to study climate effects. The climatic zones shown in Figure 3-5 help the planner select repairs since these zones are based on expected pavement performance for various amounts of moisture in the subgrade and regional temperatures [64]. The amount of rainfall in a climatic region affects the amount of water that may enter the pavement foundation.

Besides increasing the water content of the base, subbase or subgrade, rainfall affects the water table height, which may change throughout the year. The height of the water table and the soil texture affect the amount of moisture that moves from the water table to the pavement structure. Suction in silts and clays may have an effect on the moisture content of the base course when the water table is 30 feet below the pavement surface [5].

Significant moisture sources may not be a problem if gravitational orces can remove moisture from the pavement structure. Moisture removal rates are affected by the permeability of the base course and natural drainage characteristics of the airport. Since moisture decreases soil stiffness and increases the damage sustained during freeze-thaw cycles, the pavement rate of deterioration will be very high if this condition persists for long periods of time. For airfield pavements, the amount of erosion expected is often correlated with the time required to reduce the base saturation level to 50 percent [5]. The drainage time can be determined during a pavement evaluation using references 5, and 65 through 67. Based on this criteria, the base permeability can be classified as being either acceptable, marginal or unacceptable.

DECISION TREE SUMMARY 3-I-1A
CLIMATE AND DRAINAGE STUDY

TREE NODE	PATH DISCRIMINATORS
Moisture Region	Dry
	Wet OR Intermediate
High Ground Water Seepage?	Yes
	No
Water Table Depth	<= 10 ft
	> 10 ft AND < 30 ft
	>= 30 ft
Silt or Clay Subgrade?	Yes
	No
Base Layer Exists?	Yes
	No
Base Drainage Time	Marginal OR Unacceptable
	Acceptable
Subgrade Natural Drainage Index	Well OR Somewhat Excessively OR Excessively Drained
	Very Poor OR Poorly OR Imperfectly OR Moderately Well Drained
Temperature Region	Freeze OR Freeze-Thaw
	No-Freeze

CONCLUSIONS
C1. Airport Has Significant/Insignificant Moisture Sources.
C2. High Potential For Frost Heave or Significant Freeze-Thaw Damage.
C3. Temperature Does Not Support Frost Heave Conditions or Significant Freeze-Thaw Action.
C4. Subsurface Drainage Is Acceptable/Unacceptable.

The natural drainage characteristics of the underlying soil will either assist in draining the pavement structure or prevent bottom drainage into the subgrade. For agricultural reasons, most counties have maps that place land topography into one of seven drainage categories, ranging from "excessively drained" to "very poorly drained." If an airport is located in a climatic region where significant moisture sources exist and the location has poor natural drainage, a permeable base may be necessary to prevent the types of JPCP damage that were discussed in Chapter 2.

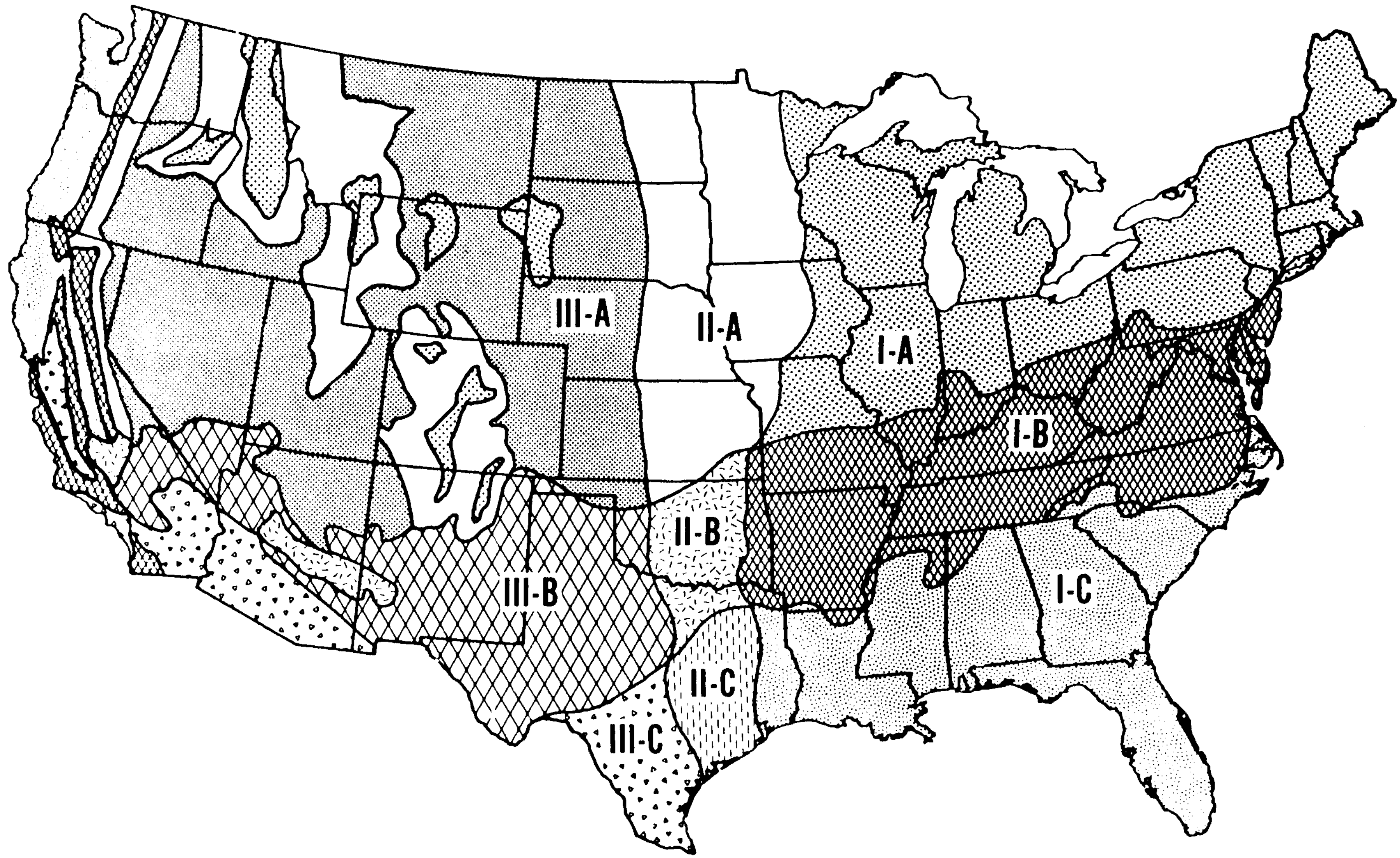
Subsurface moisture will not only weaken the pavement foundation, but may cause additional damage if the airport is located in region where freeze-thaw action occurs. The extent and types of pavement damage will depend on the temperature region shown in Figure 3-5. The most severe durability problems normally occur in regions I-B and II-B, while spring thaw damage may be more severe in colder "A" regions where frost penetrates further into the subgrade. Planners use this information to reach the conclusions shown in DTS 3-I-1A.

An example problem will illustrate how the information in a DTS can be used to arrive at one or more of the conclusions shown at the bottom of a DTS. For each node shown DTS 3-I-1A, the underlined discriminator identifies a characteristic of the climate or a subsurface drainage condition for a hypothetical airport DTS 3-I-1A also illustrates the fact that a planner may arrive at several intermediate conclusions before reaching a final conclusion about the airport climate. Any of the conclusions a planner reaches after completing an action shown in Figure 3-4 may be used to support additional conclusions drawn as subsequent planner actions are completed.

3.2.1.2.2 <u>Study Mission Aircraft And Pavement Rate Of Deterioration</u>

The next planner action in the general assessment of the airport is a review of the current mission aircraft and the pavement rate of deterioration (ROD). DTS 3-I-1B shows the decision tree nodes and path discriminators used to study the structural rate of deterioration of the JPCP. The mission status is important since the planner tries to correlate the rate of deterioration with aircraft traffic history. If the airport is going to support a new mission, the planner must assume that the new structural loads will change pavement performance and require a structural improvement to the pavement structure. Many older airports have usually gone through at least one mission change in the past. In this situation, the planner must consider the recency of the change and any change in the pavement ROD that might be related to the mission change.

FIGURE 3-5 [64]
NINE CLIMATIC ZONES BASED ON MOISTURE AND TEMPERATURE
INFLUENCE ON PERFORMANCE



The knowledge captured and represented in AIRPACS classifies a recent mission change as one that has occurred in the past five years. If a mission change has occurred, signs of structural overloading normally begin to show by the fifth year. JPCP cracking that begins to appear at the concrete surface usually occurs in a systematic pattern. Most of the cracking will be in the center of the pavement facility where the aircraft pass-to-coverage ratio is the lowest. Structural overloading caused by a recent mission change may also be checked by comparing the existing JPCP thickness to a typical thickness for each aircraft currently using the airport pavement facility.

DECISION TREE SUMMARY 3-I-1B
STUDY MISSION AIRCRAFT AND PAVEMENT RATE OF DETERIORATION

TREE NODE	PATH DISCRIMINATORS
Mission Status	New
	Changed Within Last 5 Years
	No Recent Change
Short Term ROD	Low OR Normal
	High
Existing JPCP Thickness	Less Than Typical Thickness
	Greater Than Typical Thickness
Slab Cracking Pattern	Systematic
	Localized
Long Term ROD	Low OR Normal
	High

CONCLUSIONS
C1. Structural Improvement Is Needed.
C2. Aircraft Traffic May Be Overloading Pavement Structure.
C3. Aircraft Traffic Is Not Overloading Pavement Structure.

Typical thicknesses were determined for groups of aircraft using a computer program for rigid airfield design (Waterways Experiment Station RAD807) which is based on AFM 88-6, Chapter 3 [15, 68]. To minimize the number of typical thicknesses in AIRPACS, only one thickness was selected for the critical aircraft in each of the 13 group indices (GI) shown in Appendix F. For a given number of passes, the aircraft that causes the most damage within a group is identified as the critical aircraft. Typical input values that were used to determine typical thicknesses for the critical aircraft are as follows:

(1) k = 200 psi/in
(2) E = 4,000,000 psi
(3) μ = 0.15
(4) Fighter Aircraft Design Passes = 100,000
(5) Cargo & Bomber Aircraft Design Passes = 50,000

Most of the time a typical thickness will be conservative since the thickness is selected based on the critical aircraft in each of the groups. Typical JPCP thicknesses may help the planner reach one of the three possible conclusions in DTS 3-I-1B. If there is a new mission, the planner assumes a structural improvement is needed until a subsequent player in the design process prove otherwise. If there is no new mission, the planner decides if the pavement deterioration rate is acceptable or if there is a possibility that current aircraft traffic may be overloading the pavement. If the latter is true, the pavement's structural capacity will be reviewed in further detail. Once climate, mission aircraft and pavement ROD have received a cursory review, the next area of general assessment is aircraft safety.

3.2.1.2.3 Friction Study

One of the most important pavement surface characteristics that effects aircraft safety is surface friction resistance. The U.S. Air Force uses the Mu-Meter to measure surface friction after fire trucks place water on the pavement surface. The friction results are then used to estimate the various levels of hydroplaning potential shown in DTS 3-I-1C [13].

AIRPACS uses the factors in DTS 3-I-1C to decide if friction resistance should be improved. Surface friction resistance is very important on runways and high-speed taxiways where aircraft control is crucial during landings or aborted takeoffs. In these situations, the pilot may have to brake very hard to bring the aircraft to a stop in a very short distance. Since good friction resistance is always a safety concern, most of the MAJCOM pavement engineers feel that runway grooving should always be considered, especially if there is any potential for hydroplaning.

If the surface friction resistance must be improved, grooving is one of the first options that is considered. However, grooving will only be considered if the pavement facility under consideration has not been grooved. If the cross slope is inadequate and surface microtexture is poor, an overlay may be the only alternative that adequately improves friction resistance. Besides improving the macrotexture and microtexture, an overlay in this case would increase the surface drainage rate and allow aircraft to safely use a runway when it is raining.

DECISION TREE SUMMARY 3-I-1C
FRICTION STUDY

TREE NODE	PATH DISCRIMINATORS
Expected Aircraft Braking Response	No Hydroplaning Potential OR Transitional Hydroplaning Problems
	Potential Hydroplaning Problems
	High Potential For Hydroplaning
High-speed Surface?	Yes
	No
Grooved Surface?	Yes
	No
Percent Cross Slope	<= 1/2
	> 1/2

CONCLUSIONS
C1. Surface Friction Resistance Is Good/Fair/Poor.
C2. Grooving Is Feasible.
C3. Surface Profile Is Unacceptable.
C4. Functional Overlays Are Needed.

3.2.1.2.4 Roughness Study

Another pavement characteristic that enhances aircraft safety is a smooth operating surface. Since there are many ways to define and measure surface roughness, AIRPACS relies exclusively on evaluation results to identify possible repairs (DTS 3-I-1D). At the present time, AIRPACS makes a check of the evaluation results to see if long-wavelength roughness problems have been erroneously identified for a low-speed surface. In this case, the long-wavelength roughness evaluation results are ignored.

Long-wavelength roughness only poses a significant problem on a high-speed facility, such as a runway, where the aircraft speed is greater than 100 knots [17]. But short-wavelength roughness may be a problem on any type of pavement facility. Since the wavelength may be as short as two feet, the problem may be local or it may systematically occur throughout the section.

The locations and patterns of the roughness problems significantly impact the rehabilitation alternatives that are considered during the initial assessment of the pavement. Since long wavelength roughness affects long stretches of a pavement facility, roughness occurring in pavement sections is usually corrected by placing an overlay. However, short-wavelength roughness may be corrected by slab replacement or grinding if the problems occur in a few local areas.

DECISION TREE SUMMARY 3-I-1D
ROUGHNESS STUDY

TREE NODE	PATH DISCRIMINATORS
High-speed Surface?	Yes
	No
Long-wavelength Roughness Evaluation Results	Unacceptable
	Acceptable
Short-wavelength Roughness Evaluation Results	Unacceptable
	Acceptable
Extent of Roughness	Large Area OR Entire Section
	Small Local Area(s)

CONCLUSIONS

C1. Long-wavelength Surface Roughness Is Acceptable.

C2. Short-wavelength Surface Roughness Is Acceptable.

C3. Surface Profile Is Unacceptable And A Functional Overlay Is Needed.

C4. Surface Profile Is Unacceptable In Areas.

C5. Consider Slab Replacement AND Localized Grinding.

C6. OVERALL Grinding Is Feasible.

3.2.1.2.5 FOD Potential Study

The final action in the general assessment of the airport pavement system is to study the FOD potential (DTS 3-I-1E). The objective of the FOD potential study is to determine if the level of FOD generation is acceptable for current aircraft operations. If the level of FOD generation is unacceptable and shops are not able to keep up with patching requirements, an overlay may be constructed to control FOD.

Engine susceptibility to FOD hazards is always a major concern of airfield managers. Since very few pavements have a PCI of 100 and a majority of the JPCP distresses create FOD hazards (See Table 3-2), the FOD hazard must be closely and continuously monitored at most airports. Since aircraft safety is very important, many airfield managers make a visual inspection of the pavement facilities each day to be sure no serious FOD hazards exist.

DECISION TREE SUMMARY 3-I-1E
FOD POTENTIAL STUDY

TREE NODE	PATH DISCRIMINATORS
High-speed Surface?	Yes
	No
FOD Condition Index	Excellent
	Very Good
	Good
	Fair
	Poor
	Very Poor
	Failed
Are Aircraft Towed?	Yes
	No
Aircraft Engine FOD Susceptibility	Low
	Medium
	High
Does Shop Maintenance Control FOD?	Yes
	No
Facility Use	Primary
	Secondary

CONCLUSIONS
C1. Level of FOD Generation Is Acceptable/Unacceptable.

The potential for engine damage depends on the amount of FOD generated by the pavement and an engine's susceptibility to debris on a pavement surface. FOD hazards can be assessed by calculating the FOD condition index but engine susceptibility must be based on the number of FOD-related incidents. Many factors affect the probability of engine damage due to FOD, but Figure 3-6 shows that pavement debris is one of the inputs in the flow chart that describes how engineers assess engine susceptibility and aircraft survivability from non-bird hazards [9]. It is beyond the scope of this research to discuss the various mechanisms of damage to the aircraft engine, but it is important to appreciate the following conclusions made by the Boeing Propulsion Research group [9]:

(1) For airplanes using either wing or aft body-mounted engines, non-bird FOD resulting in unscheduled engine removal (UER) is not a major life cycle cost contributor. Design constraints resulting from non-bird FOD considerations should only be approved on the basis of a cost and safety tradeoff study.

(2) Bird strike will account for 25 to 40 percent of the FOD on a new airplane with wing-mounted engines.

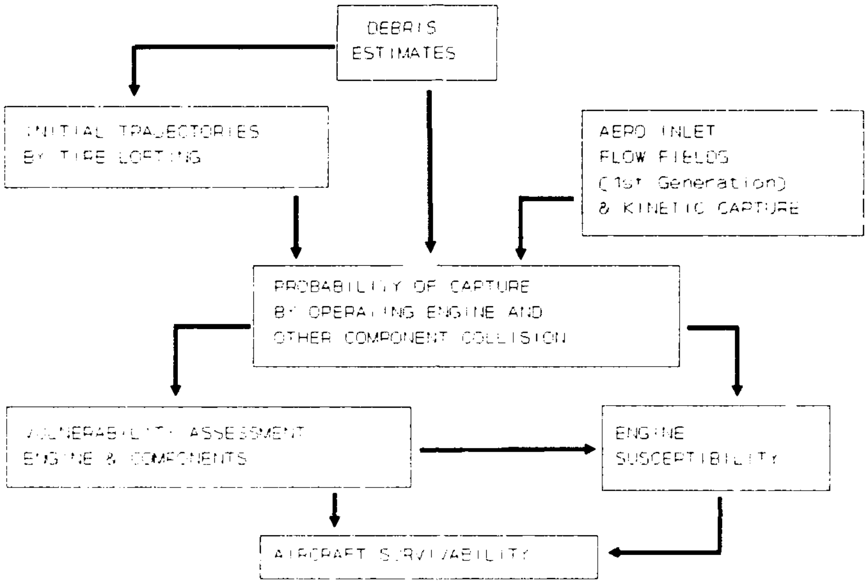
(3) A significant decrease in non-bird FOD will result from use of blow-away vortex dissipators.

(4) Engine configuration plays a significant role in UERs due to foreign object ingestion.

The validity of conclusion #4 is supported by those aircraft in the U.S. Air Force inventory that have the highest number of FOD incidents. For example, one of the most FOD-susceptible aircraft is the F-16 whose engine intake is located underneath the fuselage and is very close to the pavement surface. Pavement engineers may not be able to change the engine configuration, but they can control the amount of debris generated by pavement facilities.

Pavements that generate large amounts of surface debris normally have a low PCI and FCI, and may require a structural improvement to support current and future aircraft traffic loads. However, the U.S. Air Force has on occasion installed an overlay for the sole purpose of controlling FOD when a structural improvement was not needed. A FOD control overlay might be used if the base will be closed in less than seven years or if most flying operations will be discontinued in the near future. But if maintenance crews are sufficiently manned and have ready access to the pavement facility, routine maintenance is a better option than a non-structural overlay. Although there are very few situations where a FOD control overlay might be placed, this option should never be overlooked due to the seriousness of FOD hazards.

FIGURE 3-6
FOD INTEGRATION FLOW CHART [9]



3.2.1.3 <u>Pavement Structural Integrity</u>

After the planner completes the general assessment of an airport, the next step in the planning process is to focus on the structural integrity of the pavement section. Much of the PCI survey data can be used to determine if the pavement is structurally adequate for the current aircraft traffic. Thus, the planner will frequently review the pavement section SCI, "D" cracking distress and reactive aggregate distress, especially when a fatigue analysis is unavailable.

Decision tree summary 3-I-2F lists the factors that are used in AIRPACS to review the structural integrity of the pavement and decide if the distresses are tolerable or intolerable. Tolerable distresses are not considered serious enough to interrupt traffic operations for OVERALL repairs, so MAJOR and ROUTINE repairs are used to keep the pavement surface in an operationally acceptable condition. Extensive restoration, reconstruction and overlay become feasible methods of rehabilitation when the distresses become intolerable.

Generally, the SCI "trigger" for OVERALL repair work is higher for pavements that are more important to the airport mission. Although the factors in DTS 3-I-2F generally follow this guideline, primary runways are an exception to this line of reasoning. Most airport managers and engineers would allow the SCI of a primary runway to be lower than the SCI of a primary taxiway because they do not want to close the runway for an extended period of time. Thus, the planner will rely on routine maintenance longer and allow the SCI to fall lower than primary taxiways or aprons. The caveat to this strategy is that aircraft safety must not be compromised.

DECISION TREE SUMMARY 3-I-2F
ASSESS PAVEMENT STRUCTURAL INTEGRITY

TREE NODE	PATH DISCRIMINATORS
Structural Condition Index	> 70
	> 60 AND <= 70
	<= 60
Pavement Facility Type	Runway
	Taxiway OR Apron
Facility Use	Primary
	Secondary
Medium-Severity & High-Severity "D" Cracking	>= 40% Of Slabs In Section
	< 40% Of Slabs In Section
High Percentage of Section Area Has Reactive Aggregate Distress?	Yes
	No

CONCLUSIONS
C1. Tolerable/Intolerable Amount of Structural Distresses.
C2. Tolerable/Intolerable Climate And Material Distresses.
C3. Tolerable/Intolerable Reactive Aggregate Distresses.
C4. Pavement Has/Has No Severe Durability Problems.
C5. Structural Improvement Is Needed.

This rehabilitation philosophy usually does not apply to durability-related distresses. If the matrix structure of the concrete has deteriorated to the point where it can no longer structurally support aircraft operations, extensive rehabilitation is necessary regardless of the type of pavement facility, unless the facility is going to be permanently closed. Since severe durability problems are also a significant source of FOD debris, aircraft safety may be compromised, especially if an aircraft using the facility has engines that are highly susceptible to FOD.

DECISION TREE SUMMARY 3-I-4I
SURFACE CRACKS AND FATIGUE COMPARISON

TREE NODE	PATH DISCRIMINATORS
L/T/Diag Cracking AND Shattered Slabs	<= 5%
	> 5% AND <= 20%
	> 20%
Fatigue Analysis Available?	Yes
	No
Past Accumulated Miner's Damage	>= 0 AND <= 0.40
	> 0.40
Recent Mission Change?	Yes
	No
Past Accumulated Miner's Damage	> 0.05 AND <= 0.60
	<= 0.05 OR > 0.60
Past Accumulated Miner's Damage	>= 0.30
	< 0.30

CONCLUSIONS
C1. Fatigue Damage Is Acceptable.
C2. Fatigue Damage Is Unacceptable And A Structural Improvement Is Needed

If a concrete fatigue analysis has been conducted (DTS 3-I-4I), the results may be used to support conclusions that are drawn about the structural capacity of the pavement. If the airport traffic history has been accurately recorded, which is seldom the case, the amount of fatigue damage should correlate reasonably well with the visible surface cracks in the JPCP. If the correlation is poor, further reasoning by a planner is based on visible cracking, which is the more reliable method of estimating past concrete fatigue damage. The exception to this case is when there are few visible surface cracks, but the pavement rate of deterioration has been high due to a recent mission change.

3.2.1.4 Reconstruction And Overlay Assessment

At this point in the planning process, the planner has reviewed enough data to decide if there is a requirement for a structural improvement or safety-enhancing overlay. If a structural or safety improvement is needed, further study of the state of the pavement structure is required to determine if overlays and reconstruction are feasible methods of rehabilitation. Geometric or construction limitations, JPCP PCI, subsurface drainage and frost effects must be considered simultaneously to determine if overlay and reconstruction are feasible options (Node 6 in Figure 3-4 on p 56). There are scenarios where neither alternative is feasible despite the need for structural improvements or safety enhancements.

The surface geometry of airport pavements is a very important factor to consider if the planner is contemplating the use of an overlay (DTS 3-I-6J). In general, safety-enhancing overlays will be thinner than structural overlays so grade transitions between pavement sections and pavement facilities will not be as difficult to accommodate. But grade transition can be a problem for all types of overlays, especially when an overlay is installed on a high-speed surface such as a runway. For these facilities, the section length must be sufficient to allow for an overlay grade transition to the surface of an adjacent section. The slope of this transition must be small enough to prevent long-wavelength roughness problems from being built into the pavement facility when the section is overlaid.

If the entire pavement facility is being overlaid, grade transition problems will be encountered at runway, taxiway and apron intersections. However, AIRPACS assumes that if the entire facility is being overlaid, grade transitions at intersections are not unworkable problems. But if one or more sections are being considered for overlay, overlay feasibility will depend on the section location as well as the size of the section.

Figure 3-7 shows the possible locations of a section within a pavement facility. If the section is as wide as the pavement facility, (full-facility-width), overlays may be feasible if the section is long enough for grade transition to an adjacent keel, edge or full-facility-width section. Grade transition problems at the section ends can be accommodated by reconstructing the ends as shown in Figure 3-8.

Overlay of a keel section is possible only if the section length is sufficient for longitudinal grade transition and border sections are also overlaid. Border sections are those JPCP sections that share a longitudinal joint with the section being designed. Overlay geometry poses fewer constraints if a group of sections are considered in the planning process. If one section in the group does not need to be overlaid, it may still be economically advantageous to overlay the entire group.

DECISION TREE SUMMARY 3-I-6J
GEOMETRIC RESTRICTIONS FOR OVERLAYS

TREE NODE	PATH DISCRIMINATORS
Multiple Sections Being Considered?	Yes
	No
Is Entire Pavement Facility Being Overlaid?	Yes
	No
Feature(s) Location	Full Pavement Facility Width
	Keel Area OR Pavement Facility Edge
Are Border Sections Allowed To Be Overlaid?	Yes
	No
Facility Type	Runway
	Taxiway
	Apron
Group Length OR Section Length (Runways)	< 1000 feet
	>= 1000 feet
Group Length OR Section Length (Taxiways)	< 500 feet
	>= 500 feet
Group Width OR Length OR Section Width OR Length Is < 500 feet (Aprons)	Yes
	No

CONCLUSIONS
C1. Overlay Geometry Is Acceptable.
C2. Overlay Geometry IS Unacceptable And Overlays Are Infeasible.

FIGURE 3-7
PAVEMENT SECTION LOCATIONS

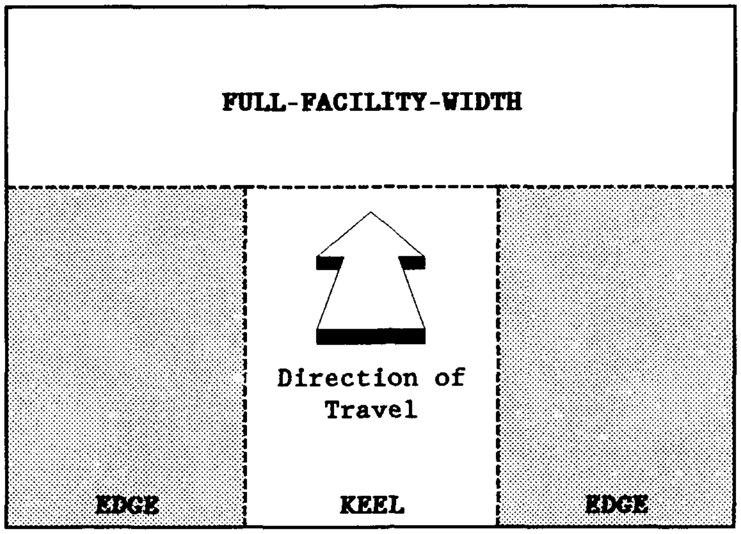
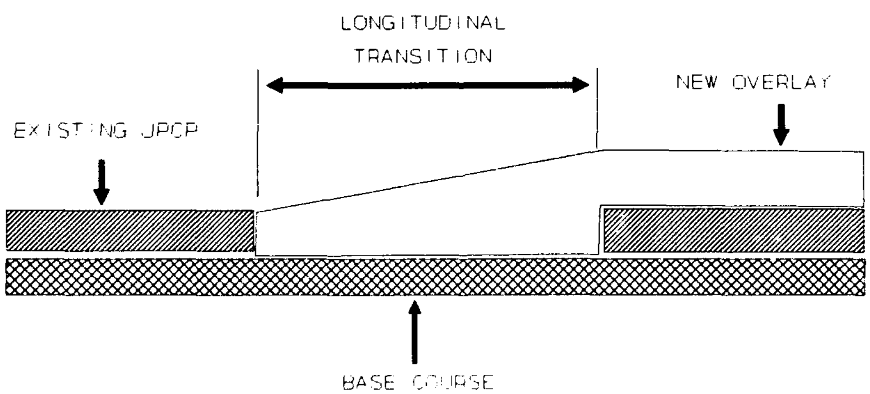


FIGURE 3-8
OVERLAY GRADE TRANSITION



An overlay does not automatically become a feasible option if a section needs a structural improvement or safety-enhancing overlay and one is geometrically feasible to construct. There are situations in which it is not reasonable to install an overlay. For example, if the pavement has failed and subsurface drainage is unacceptable, then reconstruction may be the only feasible rehabilitation alternative. The factors in DTS 3-I-6K are used to decide if overlays, reconstruction or both are feasible methods of rehabilitation.

Reconstruction is an attractive alternative because geometry is not a problem and subsurface problems can be corrected. However, if the pavement condition is relatively good, reconstruction would not be preferable even if subsurface problems exist or a structural improvement is needed. For this scenario, reconstruction is not attractive because the facility is closed for a long period of time during construction. In addition, the cost is obviously too high for the small improvement in the pavement condition. If the surface geometry is unacceptable for overlays, most MAJCOM pavement engineers will wait until more of the pavement fatigue life is consumed and then consider reconstruction.

Subsurface problems that can be corrected through reconstruction include drainage and frost problems. If the subsurface drainage is unacceptable, a permeable base course can be installed which will make longitudinal drains remove water better or make it worthwhile to repair faulty drains. If no longitudinal drains exist, reconstruction provides an excellent opportunity for the installation of a complete drainage system, which would include a permeable base course and longitudinal drains. If there is inadequate frost protection and reconstruction is feasible, thicker non-frost-susceptible base and subbase courses can be installed to protect against frost penetration.

JPC pavements may be reconstructed in a number of ways. The existing JPCP may be removed and recycled, removed and hauled to a disposal area, cracked and seated, or rubblized. In addition, the entire section does not have to be replaced. If the section is very wide and only the center lanes of the section receive heavy traffic, then it may be more economical to replace only the center lanes. The Planner DPDM looks at all methods of reconstruction and determines what methods are feasible. After all feasible types of reconstruction are identified, the next step in the planning process is to select feasible types of overlays when overlays are feasible.

DECISION TREE SUMMARY 3-I-6K
PAVEMENT SYSTEM ASSESSMENT

TREE NODE	PATH DISCRIMINATORS
Is Structural Improvement Needed?	Yes
	No
Is Overlay Geometry Acceptable?	Yes
	No
PCI Value	<= 40
	> 40 AND < 60
	>= 60
Is Subsurface Drainage Acceptable And No Systematic Frost Heave Exists And Adequate Frost Protection Exists?	Yes
	No
Is Subsurface Drainage Acceptable?	Yes
	No
Keel Section?	Yes
	No
Full-Facility Width Section And Section Width > 100 Feet?	Yes
	No

CONCLUSIONS
C1. Overlays Are Feasible/Infeasible.
C2. Recycling And Standard Reconstruction Are Feasible/Infeasible.
C3. Keel Replacement Is Feasible/Infeasible.
C4. Crack & Seat Is Feasible/Infeasible.

3.2.1.5 Feasible Overlay Types

Decision tree summary 3-I-8L shows the factors the Planner DPDM considers when it selects feasible types of overlays for a JPCP section. This research considers both Portland cement concrete (PCC) and asphalt concrete (AC) overlays as potential rehabilitation options. Bonded and unbonded JPCP overlays are considered for structural improvements and for safety enhancement. However, a

DECISION TREE SUMMARY 3-I-8L
SELECT TYPES OF OVERLAYS

TREE NODE	PATH DISCRIMINATORS
Are Overlays Feasible?	Yes No
Overlay Category	Safety-enhancing Structural
PCI Rating	Excellent Very Good Good Fair Poor Very Poor OR Failed
Number of "D" Cracked Slabs In Section	Low Severity >= 15% OR Medium Severity >= 1% OR High Severity >= 1% Low Severity < 15% AND Medium Severity < 1% AND High Severity < 1%
Reactive Aggregate?	Yes No
Number of Scaling Slabs In Section	Low Severity >= 30% OR Medium Severity >= 1% OR High Severity >= 1% Low Severity < 30% AND Medium Severity < 1% AND High Severity < 1%
Facility Type	Runway Taxiway Apron
Is Friction Resistance Unacceptable?	Yes No
Is Level of FOD Generation Unacceptable?	Yes No
Is Surface Profile Acceptable? (Determined During Friction And Roughness Studies)	Yes No
Is An Aircraft Arresting System Located In Section?	Yes No
Is Section Within 1000 Feet of Runway End?	Yes No
Feasible Overlay Area of Sections?	>= 1/2 of Total Group Area < 1/2 of Total Group Area

CONCLUSIONS

C1. Bonded JPCP Overlay Is Feasible/Infeasible For Structural Improvements/Profile/Corrections/Friction Enhancement.

C2. Unbonded JPCP Overlay Is Feasible/Infeasible For Structural Improvements/Profile Corrections/Friction Enhancement.

C3. Asphalt Overlay Is Feasible/Infeasible For Structural Improvements/Profile Corrections/Friction Enhancement/FOD Control.

PCC overlay is not used to control the level of FOD because it is too expensive. AC overlays included in AIRPACS include porous friction courses (PFC) and dense-graded hot mixes. A PFC can only be used to improve friction resistance, but a dense-graded mix can be used for all types of improvements. Although more than one type of overlay may correct a problem, there are usually only one or two overlays that are appropriate for a specific pavement surface condition and section location.

Another factor that must be considered when selecting an overlay is that the asphalt cement in asphalt concrete is soluble in jet fuel. Therefore, asphalt concrete is seldom used in areas where fuel spillage may occur (e.g., runway ends, aprons). AC is less wear-resistant than PCC, so it is also seldom used in areas where an abrasion resistant surface material is required. For the same reason, AC is never placed underneath an aircraft arresting system such as a BAK-12. A BAK-12 system has a steel cable that is held two inches above the pavement surface with rubber "donuts." Whenever an aircraft passes over a BAK-12 system, the cable is pushed down, causing a high rate of wear if the pavement surface material is not durable. Most of the time an arresting system is located within 1000 feet of the end of a runway.

PCC overlays are frequently used in lieu of AC overlays in areas where fuel spillage is likely. Bonded PCC overlays are normally considered when the section PCI is greater than 55 (good condition). Since the overlay and existing slabs are assumed to act as a monolithic slab, the existing surface must be in good condition to develop a strong bond. Therefore, bonded overlays generally are not feasible if significant durability problems exist or extensive repair is necessary to restore the pavement surface to acceptable condition. If extensive repairs are required, a bonded overlay may be prohibitively expensive which leaves an unbonded overlay as the only feasible alternative in areas where jet fuel spillage is possible.

As the condition of the existing JPC pavement gets worse, an unbonded overlay becomes more attractive than other types of overlays. Unless an AC overlay is used to temporarily control FOD, it will not be used when the PCI is low since reflective cracking will eventually become a serious maintenance problem. Although an unbonded overlay is a feasible alternative when the PCI is low, many MAJCOM pavement engineers prefer reconstruction if a structural improvement is needed. They argue that the thickness of an unbonded overlay is almost as thick as a reconstructed JPCP section and that too many overlay geometric restrictions exist for most airport pavement facilities.

If a structural overlay is required and is feasible to construct, most safety-enhancing requirements can be included in the design of the structural overlay. Friction resistance can be improved by insuring the aggregate selected for the mix design will enhance microtexture and that the surface finishing technique will improve macrotexture characteristics. If FOD is a severe problem, all structural overlays will eliminate this problem. For most situations, short-wavelength and long-wavelength roughness problems can also be corrected when a structural overlay is constructed. If long-wavelength roughness problems exist, a separation layer may have to be used in some areas if the structural overlay thickness is not sufficient to correct the surface profile.

While a structural overlay may also improve aircraft safety, a safety-enhancing overlay normally does not significantly increase the load-carrying capacity of the JPCP. For example, the total thickness of a porous friction course (PFC) placed on top of an AC layer is usually 1.5 to 2 inches thick, so it provides little structural benefit in airport pavements where typical JPC layers are normally greater than 10 inches thick. Although overlays are seldom constructed to control FOD, the nominal thickness of the overlay would be similar to a PFC and would also provide little structural benefit. Finally, overlays that are designed to correct roughness problems often provide little structural benefit unless a long-wavelength roughness problem requires a significant overlay thickness, which is seldom the case. For these reasons, AIRPACS ignores the structural benefit of a safety-enhancing overlay.

3.2.1.6 Drainage Improvements

The primary objective of the drainage knowledge captured in AIRPACS is to insure that drainage repairs or improvements are not overlooked in the design process. The reliability of the drainage improvements recommended by AIRPACS depends on the quality of the drainage evaluation. A drainage evaluation knowledge-base is not part of AIRPACS, but the Planner knowledge-base uses evaluation results which are input by the KBES user. Possible drainage improvements include cleaning or repairing existing drainage pipe and filter material, installation of a permeable base course, shoulder repair, catch basin repair and installation of new drainage pipe (DTS 3-I-8M).

DECISION TREE SUMMARY 3-I-8M
SELECT DRAINAGE OPTIONS

TREE NODE	PATH DISCRIMINATORS
Is Subsurface Drainage Acceptable?	Yes
	No
Is Reconstruction Feasible?	Yes
	No
Do Longitudinal Drains And Filters Exist?	Yes
	No
Do Transverse Drains And Filters Exist?	Yes
	No
Drainage Pipe Capacity	Marginal OR Unacceptable
	Satisfactory
Does Section Have Catch Basins?	Yes
	No
Does Section Have Shoulder(s)?	Yes
	No
Catch Basin Condition	Marginal OR Unacceptable
	Satisfactory
Is Overlay Feasible?	Yes
	No
Shoulder Condition	Marginal OR Unacceptable
	Satisfactory

CONCLUSIONS
C1. Install/Do Not Install Longitudinal Drains And Filters.
C2. Install/Do Not Install Transverse Drains And Filters.
C3. Install Permeable Base Course.
C4. Repair/Do Not Repair Longitudinal Drains And Filters.
C5. Repair/Do Not Repair Transverse Drains And Filters.
C6. Repair/Do Not Repair Catch Basins.
C7. Repair/Do Not Repair Shoulder(s).

AIRPACS does not recommend installing longitudinal drains on an airfield unless the pavement facility has a base or subgrade with satisfactory permeability. Since airport pavement facilities may be very wide, the base or subgrade must be permeable enough to allow the forces of gravity to reduce the saturation level to 50 percent in 10 days [11]. If subsurface drainage is unacceptable and reconstruction is feasible, the pavement engineers should use this opportunity to install a permeable base. When a permeable base is installed, longitudinal drains and filters should be installed, or repaired if they are not functioning properly.

A shoulder in good condition is important since it transports surface water to the longitudinal drains and further away from the heavy traffic areas of the pavement facility. If a pavement facility has catch basins that need repair, the basins should be repaired to prevent standing water from entering the pavement subsurface via the joints in the pavement. If a pavement section is going to be overlaid, the catch basins must be raised to the finished elevation of the pavement surface. Although it is not difficult to identify catch basin, subsurface drainage pipe and shoulder repairs in the planning process, it is easy to overlook these repairs when other rehabilitation alternatives are being considered. These repairs may be expensive, but the investment in drainage improvement may significantly extend the life of pavement in areas that have significant amounts of moisture.

3.2.1.7 Maintenance And Restoration

Up to this point, the discussion has focused primarily on OVERALL repairs, but the most prevalent repairs on an airfield are ROUTINE and MAJOR repairs. There are many ways to define what work constitutes maintenance and what work constitutes restoration. As Table 3-3 (p. 39) shows, several types of repairs may be appropriate for a JPCP distress. This research differentiates between maintenance and restoration by the order in which the repairs in Table 3-3 are selected, as shown in Table 3-5. If two methods of repair are appropriate for a given distress, restoration work will select the repair which improves the PCI the most while maintenance work selects the repair method that is the most expedient.

The maintenance methods applied in AIRPACS also depend on the severity of the distress. For routine maintenance, all repair methods shown in Table 3-5 are selected for all severity levels. However, emergency maintenance includes repairs for only high-severity PCI distresses while critical maintenance includes repairs for high- and medium-severity PCI distresses. These maintenance categories allow AIRPACS to present various levels of repair that are appropriate for the time a facility may be closed or for prioritizing maintenance work. For example, runways usually cannot be closed for extended periods of time, so repair crews usually repair the most severe distresses in the most expedient manner. Maintenance categories will also help prioritize work in those situations in which the crew is unable to keep up with required maintenance due to the number of pavement facilities that are experiencing a high rate of deterioration.

TABLE 3-5
REPAIR PRIORITIES

MAINTENANCE	RESTORATION
1. Crack Sealing	1. Slab Replacement
2. Joint Resealing	2. Full-Depth Repair
3. Partial-Depth Repair	3. Partial-Depth Repair
4. Full-Depth Repair	4. Joint Resealing
5. Slab Replacement	5. Crack Sealing
6. Undersealing	6. Undersealing
7. Grinding	7. Grinding
8. Slab Jacking	8. Slab Jacking
9. Do Nothing	9. Do Nothing

Two additional repair methods used in restoration work that are not addressed in Table 3-3 include joint load transfer restoration and joint shape-factor restoration (DTS 3-I-8N). Joint load transfer restoration normally involves installation of dowel bars in joints where the aggregate interlock no longer provides sufficient load transfer. This alternative may also be used to correct load transfer distresses, such as dowel "lock-up" or keyway shear failure. Methods of installing load transfer devices are discussed in reference 65. Since joint load transfer restoration is expensive, this repair method is not preferred if the pavement life is rapidly deteriorating due to significant durability problems. If durability is a serious problem and a structural improvement is needed, it would be better to use a structural overlay or reconstruct the pavement feature.

DECISION TREE SUMMARY 3-I-8N
SELECT M&R OPTIONS

TREE NODE	PATH DISCRIMINATORS
Joint Shape Factor	Marginal OR Unacceptable
	Satisfactory
Are Climate And Material Distresses Tolerable?	Yes
	No
Are Reactive Aggregate Distresses Tolerable?	Yes
	No
Percent of Joints That Are Spalled	<= 25%
	> 25%
Section Location	Facility Edge
	Keel OR Full-Facility-Width
Does Pavement Have Severe Durability Problems?	Yes
	No
Do Dowel "Lock-up" or Keyway Shear Failure Distresses Exist?	Yes
	No
Is Load Transfer Efficiency Known?	Yes
	No
Are Structural Improvements Needed?	Yes
	No
Load Transfer Efficiency	< 70%
	>= 70%
Load Transfer Efficiency	< 50%
	>= 50%

CONCLUSIONS
C1. Joint Shape-Factor Restoration Is Feasible/Infeasible.
C2. Joint Load Transfer Restoration Is Feasible/Infeasible.

Joint load transfer restoration is especially attractive when structural improvements are needed, existing joint load transfer efficiency is low, and the existing JPCP has a significant amount of fatigue life remaining. In this case, the reduction in edge stresses may have a significant impact on pavement performance. This stress reduction may be sufficient to accommodate all future aircraft traffic for the remainder of the pavement life. This repair may be especially attractive if the section is a keel section or a full-facility-width section where the pass-to-coverage ratios are the lowest. A reduction in pavement edge stresses in these areas will have a greater impact on JPCP performance improvement.

Joint sealant reservoir reshaping may be done to improve joint sealant performance by constructing a new joint reservoir with dimensions that are appropriate for the sealant material being used and the existing joint spacing. This will keep the sealant strain within acceptable limits as the slabs expand and contract. This method has been used by some MAJCOM pavement engineers as an interim repair for "D" cracked pavements. But most MAJCOM pavement engineers prefer not to use this repair if there are severe reactive aggregate problems in the pavement. In this situation, the benefits of good joint sealant performance are overshadowed by the high amounts of FOD caused by reactive aggregate distress.

3.2.2 Contractor

The contractor design process decision maker (DPDM) is the next player in the overall design process. Contractors should always be included in the design process because construction methods for a rehabilitation alternative directly impact project cost, work quality and safety. At the present time, the contractor knowledge-base in AIRPACS is small, but the knowledge reflects some of the primary concerns of the contractor. The central theme in this knowledge base is that contractors experienced with airport pavement repair can build a high-quality pavement given ample construction time.

New problems may be created if feasible rehabilitation alternatives are not constructed properly. The quality of the work is influenced by length of the construction period and by the experience of the contractor. For most types of repairs, the U.S. Air Force has found that prior airfield rehabilitation experience is critical to good pavement performance.

Many experienced pavement contractors have acquired their experience from road and parking lot projects. However, the specification standards for road and parking lot construction are less stringent than the standards for airport pavement construction. The standards are especially stringent for runways, where aircraft speeds are much higher than on other pavement features on the airfield. For these reasons, the U.S. Air Force has concluded that the probability of poor construction is very high if the contractor has little or no previous airfield pavement experience with a particular repair.

DECISION TREE SUMMARY II
CONTRACTOR CONCERNS

TREE NODE	PATH DISCRIMINATORS
Alternative Type	Overlay
	Reconstruction
	Restoration OR Maintenance
Is Subsurface Drainage Acceptable?	Yes
	No
Required Construction Expediency	Fast Track
	Normal
Local Contractors With Experience	Yes
	No
Overlay or Reconstruction Yardage	>= 35,000
	< 35,000
Job Scope	Large
	Small

CONCLUSIONS
C1. Alternative Is Approved For Construction.
C2. Alternative Is Not Approved For Construction.
C3. Alternative Is Reluctantly Approved For Construction.

The scope of work and the local contractor experience are two factors that AIRPACS uses to determine when an experienced contractor might bid on a rehabilitation project (DTS II). There is a good chance that a local contractor will bid on a project if that contractor has experience with the alternative being considered. However, if there is not an experienced contractor in the area, the engineer should attempt to draw a contractor from outside the local area. This could be accomplished by providing a scope of work that is large enough to make it economically feasible for the contractor to mobilize and relocate to the construction site. When repair options are being considered for a small project, the best decision is to select only those types of repairs that local contractors have constructed before.

Besides the scope of work, contractors consider other factors before they decide to bid on a project. The construction period is always a key issue, especially if the alternative being considered is reconstruction and the existing subsurface drainage is unacceptable. If this is the case, a contractor may not bid on a project when fast-track construction is required. Even if adequate time is available for reconstruction projects where subsurface drainage problems exist, contractors may be reluctant to bid on that project because they may not be protected from all hidden costs. In this situation, contractors are concerned that subsurface courses may not provide an adequate construction platform.

During an interview with Mr. Yrjanson from the American Concrete Pavement Association, Mr. Yrjanson stated that a contractor's preferred alternative for structural improvements is the JPCP unbonded overlay. For this alternative, little surface preparation is required and the existing JPCP provides an excellent construction platform. Mr. Yrjanson also provided some rules of advice which are included in the contractor knowledge-base. If reconstruction is being considered, the contractor should always have the option to recycle the JPC layer since it is very difficult for the planner to anticipate all the problems that the contractor may encounter during reconstruction. Recycled material that is used in the new mix design or as a permeable base may minimize potential aggregate availability or landfill disposal problems.

Mr. Yrjanson offered additional advice for JPCP joint construction which is a major cost in JPCP construction. To obtain a high joint stress load transfer efficiency (SLTE), most contractors prefer to construct a doweled joint. Construction equipment used today can rapidly and accurately drill holes for the insertion of dowels. However, pavement engineers should use care when preparing specifications to insure that tolerances for dowel placement are not unreasonable. Doweled joints are preferred over keyed and thickened-edge joints because of the difficulty of constructing those joints. The type of joint that contractors have the most difficulty constructing is the expansion joint since the joint width must be constant for the entire slab thickness. Therefore, these types of joints should be kept to a minimum in the rehabilitation design.

One of the players in the design process who will be watching the contractor very closely during construction is the airfield manager. Since airfield managers are very concerned about airport traffic interruptions during construction, it is important to include their concerns in the design process.

3.2.3 Airfield Manager

An airfield manager is concerned with aircraft safety and operations during construction. The amount of FOD generated during construction is one of the primary safety concerns of an airfield manager. The author is aware of the concerns of an airfield manager since he designed projects that involved apron reconstruction, taxiway keel replacement and random slab replacement for a U.S. Air Force base that had only one parallel taxiway. When alternate taxi routes were being established to accommodate the construction work, the predominant concerns of the airfield manager were; (1) how much debris would be generated, (2) how clean could the contractor keep the immediate work area, (3) how long was the construction period and (4) how close would aircraft be to the work area during taxi operations (DTS III).

An airfield manager is concerned with the length of the construction period because it effects the amount of time aircraft are exposed to potential safety hazards and possible sortie reduction. Sortie reduction can be a dominant factor in the decision making process, especially at airport hubs where commercial airlines may lose significant amounts of revenue. AIRPACS looks at the type of construction, subsurface conditions and allowable pavement facility closure time to determine if an airfield manager would approve a rehabilitation alternative. Subsurface condition is a key factor since a contractor needs a good construction platform for reconstruction and drainage work. An exposed base, subbase or subgrade may not support equipment if rainfall saturates these subsurface layers. Although soil stabilization techniques may be used to increase the strength of the construction platform, these techniques may be expensive and are not always effective.

DECISION TREE SUMMARY III
AIRFIELD MANAGER CONCERNS

TREE NODE	PATH DISCRIMINATORS
Alternative Type	Overlay OR Reconstruction
	Drainage
	Restoration OR Maintenance
Drainage Work Options	Repair Catch Basins, Repair Longitudinal Drains Install Longitudinal Drains, OR Repair Shoulder
	Install Base Course, Install Transverse Drains, OR Repair Transverse Drains
Facility Type	Runway
	Taxiway OR Apron
Allowable Closure Time	Overnight
	1 to 10 Days
	More Than 10 Days
Fast-Track Construction?	Yes
	No
Is Subsurface Drainage Acceptable?	Yes
	No
Proximity of Aircraft To Work Site	< 100 ft
	>= 100 ft
Is Large Amount of Debris Generated During Demolition?	Yes
	No
Alternative Methods With Lengthy Construction Periods	Reconstruction
	Other Types of Work

CONCLUSIONS
C1. All Options Are Operationally Acceptable.
C2. No Option Is Operationally Acceptable.
C3. Overlay Options Are Operationally Acceptable.
C4. Reconstruction, Base Installation and Transverse Drainage Work Are Operationally Acceptable.
C5. Reconstruction, Base Installation and Transverse Drainage Work Are Not Operationally Acceptable.
C6. All Work Is Safe To Construct.
C7. All Work Other Than Reconstruction Is Safe To Construct.
C9. Standard Reconstruction And Recycling Are Safe To Construct.
C10. Standard Reconstruction And Recycling Are Not Safe To Construct.

If the construction work associated with a specific rehabilitation alternative does not compromise aircraft safety and sortie generation remains at an acceptable level, the airfield manager should approve any alternative that has been approved by the planner and contractor. At this point in the design process, the planner has identified all feasible rehabilitation options for each pavement section under design. In addition, the contractor has identified those feasible repairs that have a high probability of being constructed by a contractor with prior experience in airport pavement rehabilitation. Once the airfield manager approves those alternatives, the designer can proceed with rehabilitation design tasks.

3.2.4 Designer

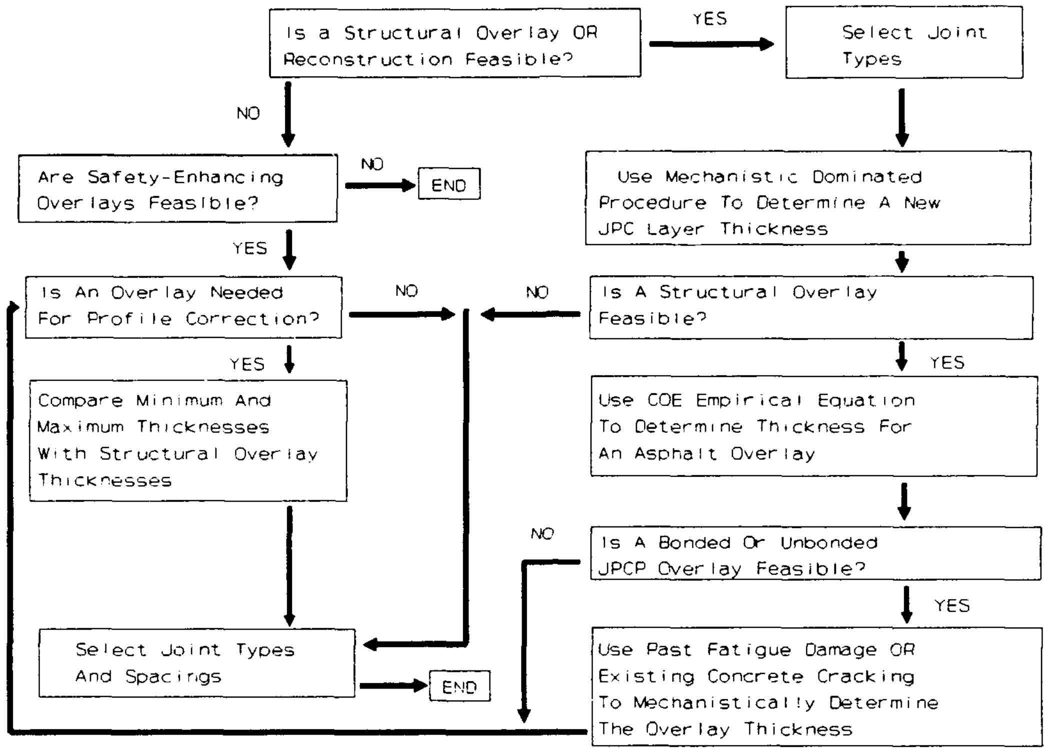
The designer is the player in the rehabilitation design process who depends most on decision-making tools to complete the work tasks. AIRPACS designer activities include structural thickness design of reconstruction and overlay alternatives, selection of joint types, and determination of joint spacing. This research focuses on design activities for these rehabilitation alternatives since they are difficult to design. In addition, these are the areas in a JPCP design that need the most improvement in light of recent advances made in the research field. In the following sections, readers familiar with the FAA and U.S. Air Force design procedures [7, 15] will recognize recent design knowledge in JPCP thickness and joint design that has been captured and represented in AIRPACS.

The first task of the designer is to review all rehabilitation alternatives that have been approved by the planner, constructor and airfield manager. From this list, the designer will determine the thickness required for options intended to improve the load-carrying capacity of the pavement. The load-carrying capacity can be increased by reconstructing the existing JPCP or placing an overlay. Figure 3-9 provides an overview of the thickness and joint spacing design procedure AIRPACS uses for JPCP rehabilitation. The following sections discuss the types of knowledge used for each design activity in Figure 3-9.

3.2.4.1 <u>Joint Type Selection</u>

If a structural overlay or reconstruction is feasible, the first design action is to select the type of joints that will <u>control</u> the thickness design for a new JPC layer and structural overlay. Joint types must be selected before

FIGURE 3-9
JPCP THICKNESS AND JOINT SPACING DESIGN PROCEDURE



thicknesses are determined because deflection load transfer efficiencies (DLTE) are required in the thickness design (DTS IV). For reconstruction or an unbonded JPCP overlay, the DLTE is always based on the joint types specified by the user.

If a bonded JPCP or an AC structural overlay is being considered, the existing joints will usually contribute the most to load transfer so the DLTE is selected based on the Falling Weight Deflectometer (FWD) joint evaluation results. When joint evaluation results are not available, a DLTE of 85 percent is used if all of the existing joints are doweled. If any of the existing joints rely on aggregate interlock or keyways for load transfer, the DLTE is estimated using Foxworthy's model for DLTE for each of the four seasons.

Although the existing joints usually control the design DLTE for a bonded JPCP or an AC overlay, AIRPACs will make recommendations for the joints in the overlay. The KBES selects aggregate interlock, or dummy, contraction joints for all joints in these overlays. If an AC structural overlay is feasible, sawed and

DECISION TREE SUMMARY IV
JOINT TYPE SELECTION AND DESIGN DLTE DETERMINATION

TREE NODE	PATH DISCRIMINATORS
Is Reconstruction OR An Unbonded JPCP Structural Overlay Feasible?	Yes
	No
Is A Bonded JPCP OR An AC Structural Overlay Feasible?	Yes
	No
Are FWD Determined DLTE Evaluation Results Available?	Yes
	No
Existing JPCP Joint Types	All Joint Types Are Doweled
	Some Joints Rely On Aggregate Interlock OR Keyways For Load Transfer
User-Specified Joint Types	All Joint Types Are Doweled
	Some Joints Rely On Aggregate Interlock OR Keyways For Load Transfer

CONCLUSIONS
C1. All Bonded JPCP And AC Overlays Joints Will Be Dummy Joints.
C2. All Joint Types Are As Specified By User.
C3. Use Lowest DLTE Of All Existing JPCP Joints.
C4. Use DLTE Of 85 Percent For All Joints For All Four Seasons.
C5. Use Foxworthy's Model And Regional Mean Daily Temperatures For Each Season To Determine DLTEs.

sealed joints are always recommended. Since AIRPACS does not permit the use of dowels in bonded JPC overlays, dummy contraction joints are selected. For a construction joint in the overlay, there is no load transfer across the joint since aggregate interlock does not exist.

3.2.4.2 Material Property Selection

After the new and existing joint types have been reviewed to determine the design DLTE, material properties can then be selected. The PCC modulus of elasticity "Ec" and rupture "Mr," and the effective modulus of subgrade reaction "k" are required for thickness designs. The effective "k" value that is used in the design occurs at the bottom of the slab. Asphalt concrete properties are not required since AIRPACS uses the Corps of Engineers (COE) empirical equation for AC overlays.

For bonded JPCP and AC overlays, the existing JPCP "Ec" and "Mr" values and the existing "k" value are always used to determine the JPC layer thickness (DTS V). Existing JPCP and base (or subgrade if no base is exists) properties are also used to determine unbonded overlay thicknesses unless the free edge stress in the unbonded overlay is greater than the free edge stress in the existing JPCP. In this case, user-specified "Ec" and "Mr" new design values are used to design the unbonded JPCP overlay.

3.2.4.3 Single-Layer Thickness Design

All thickness designs in AIRPACS are based on the thickness of a single JPC layer that will support future aircraft traffic. The single JPC layer thickness is determined using a mechanistic procedure that either includes or excludes past fatigue damage (Figure 3-10). Hereafter, this thickness is referred to as either a fatigued single layer (FSL) or a new single layer (NSL). The NSL thickness is the new reconstruction thickness that is used for all types of reconstruction. If the COE's unbonded overlay equation is abandoned, the NSL thickness also represents the unbonded JPCP overlay thickness.

When the stiffness (Eh^3) of one JPC layer is much larger than the stiffness of the other JPC layer in an unbonded JPCP overlay, that layer provides the greatest contribution to the load-carrying capacity of the pavement. Therefore, a designer will make critical decisions based on the stiffness of each layer and the ratio of the unbonded JPCP overlay "Eh_t" to the existing JPCP "Eh_b."

DECISION TREE SUMMARY V
MATERIAL PROPERTY SELECTION FOR THICKNESS DESIGN

TREE NODE	PATH DISCRIMINATORS
Is Reconstruction Feasible?	Yes No
Type Of Overlay	Bonded JPCP AC Unbonded JPCP
Is "Eh^3" Of Unbonded JPCP Overlay Twice As Large As "Eh^3" Of Existing JPCP?	Yes No
Is "Eh" Of Unbonded JPCP Overlay Less Than "Eh" Of Existing JPCP?	Yes No

CONCLUSIONS

C1. Fatigued Single Layer JPCP Thickness Determined Using:
- (a) Existing JPCP "E" And "Mr" Values.
- (b) Existing Base Or Subgrade "k" Value.
- (c) Past Fatigue Damage.

C2. Fatigued Single Layer JPCP Thickness Determined Using:
- (a) User-Specified New Design JPCP "E" And "Mr" Values.
- (b) Existing Base Or Subgrade "k" Value.
- (c) Past Fatigue Damage.

C3. New Single Layer JPCP Thickness Determined Using:
- (a) User-Specified New Design JPCP "E" And "Mr" Values.
- (b) Use Subgrade "k" Value of 200 psi/in.
- (c) Past Fatigue Damage NOT Included.

C4. New Single Layer JPCP Thickness Determined Using:
- (a) User-Specified New Design JPCP "E" And "Mr" Values.
- (b) Existing Base Or Subgrade "k" Value.
- (c) Past Fatigue Damage NOT Included.

FIGURE 3-10
SINGLE LAYER JPCP THICKNESS DESIGN PROCEDURE

STEP 1: Identify Aircraft Using Pavement Section, Average Annual Passes Of Each Aircraft, Pass-To-Coverage Ratios and Aircraft Main Gear Spacing.

↓

STEP 2: Select PCC "E" And "Mr" Values and Base Or Subgrade "k" Value.

↓

STEP 3: Determine Seasonal Deflection Load Transfer Efficiencies (DLTE).

↓

STEP 4: Compute Radius Of Relative Stiffness, ℓ (EQN 3.1).

↓

STEP 5: Compute Equivalent Single-Wheel Radius (ESWR) For Each Aircraft.

↓

STEP 6: Determine Free Edge Stress For Current Trial JPC Layer Thickness (EQN 3.2).

↓

STEP 7: Compute Seasonal Stress Load Transfer Efficiencies Using Figure 3-2 (SLTE).

↓

STEP 8: Compute Slab Edge Stresses Along Transverse Joint For Each Aircraft.

↓

STEP 9: Compute Future Miner's Damage For Each Aircraft (EQNs 3.6 & 3.7).

↓

STEP 10: Identify Critical Aircraft As The Aircraft Causing The Most Future Damage.

↓

STEP 11: Determine Future Damage That Each Non-Critical Aircraft Will Cause At The Critical Aircraft's Main Gear Location On The Pavement Section (EQNs 3.8 & 3.9).

↓

STEP 12: Determine Total Cumulative Damage Of All Aircraft. Include Past Cumulative Damage If Applicable (EQN 3.7).

↓

STEP 13: If Total Damage Is Between 0.90 And 1.05, **STOP** - Current Thickness Is Acceptable.

↓

STEP 14: Increase Or Decrease Current Trial Thickness.

↓

STEP 15: If Material Properties Must Be Changed, Repeat Procedure Starting At Step 2. Otherwise, Repeat Procedure Starting At Step 4.

FIGURE 3-11
STIFFNESS AND FREE-EDGE-STRESS RATIO COMPARISONS FOR AN UNBONDED OVERLAY

$E_{pcc_{bot}}$ (10^6 psi)	$E_{pcc_{top}}$ (10^6 psi)	PCC Top Layer Thickness (inches)					
		10		12		14	
		Eh^3 Ratios	Bending σ Ratios	Eh^3 Ratios	Bending σ Ratios	Eh^3 Ratios	Bending σ Ratios
6	6	0.58	0.83	1.00	1.00	1.59	1.17
	4	0.39	0.56	0.67	0.67	1.06	0.78
4	6	0.87	1.25	1.50	1.50	2.38	1.75
	4	0.58	0.83	1.00	1.00	1.58	1.17

NOTES: (1) Ratios compare JPCP overlay parameters to existing JPCP parameters.
(2) For each cell, free edge bending stress and "Eh" ratios are equal.

Figure 3-11 shows the results of 12 ILLI-SLAB runs for the main gear of a B-52 loaded on the longitudinal slab edge with no load transfer between slabs. The notes for this figure highlight the fact that "Eh" always indicates which layer will have the largest flexural stress. Figure 3-11 also shows that the free edge stress in the unbonded JPCP overlay is higher than the stress in the existing JPCP when the overlay is more than twice as stiff as the existing JPC layer. These facts are used in the single-layer thickness design procedure (Figure 3-10) for the unbonded JPCP overlay alternative.

If the thickness of an unbonded JPCP overlay increases to the point where the overlay is twice as stiff as the existing JPCP, the empirical overlay equation is abandoned and the unbonded overlay is designed as a NSL JPCP. In this case, the user-selected design "Ec" and "Mr" material properties are used in the design of an unbonded JPCP overlay, but AIRPACS will use a "k" value of 200 instead of the actual base or subgrade "k" value. A "k" value of 200 is a wise choice to use when this rare situation occurs.

3.2.4.4 Using A Single-Layer Thickness To Compute An Overlay Thickness

Single-layer thicknesses are used to determine overlay thicknesses for AC overlays, JPCP bonded overlays, and JPCP unbonded overlays when the JPCP unbonded overlay is not designed as a new JPCP. The following section explains how the Corps of Engineer's empirical overlay equations have been represented in AIRPACS.

If the asphalt empirical overlay equation (Equation 3.11) is used, a condition factor must be determined for the existing JPCP. Rather than allowing the user to subjectively select the condition factor, C_b, the structural condition index (SCI) is used to select a JPCP condition factor for an AC overlay (Figure 3-12) [6]. Shahin and Darter introduced this method of selecting a condition factor to minimize the variance associated with condition factor selection.

Another empirical factor that must be determined before the COE AC overlay equation can be used is the "F" factor [6, 7, 14, 15]. The "F" factor indicates the tolerable amount of cracking in the JPCP when an AC overlay is constructed. Many agency design manuals include graphs which determine the "F" factor as a function of aircraft traffic and the "k" value beneath the JPC layer [7, 15]. Unless the number of coverages or average annual passes is relatively low for an airport, the "F" factor in these graphs is somewhat insensitive to changes in aircraft traffic. Thus, AIRPACS uses the graph in the Navy design manual to select the "F" factor as shown in Figure 3-13 [6]. Once the JPCP condition factor, C_b, and the "F" factor are known, AIRPACS can determine the AC overlay thickness using the existing JPCP thickness and the NSL JPCP thickness.

The FSL JPCP thickness includes past fatigue damage and is used to compute the thickness for a JPCP bonded overlay and a JPCP unbonded overlay when the overlay is not twice as stiff as the existing JPCP. Since past fatigue damage has already been accounted for in the FSL thickness, the C_r condition factor shown in Equation 3.10 is not used in the AIRPACS knowledge-base. Therefore, the JPCP bonded overlay thickness is the difference between the existing JPCP thickness and the FSL JPCP thickness computed using Figure 3-10. Likewise, the JPCP unbonded overlay thickness is computed using the 2nd order form of equation 3.10.

3.2.4.5 Joint Spacing Recommendations

After all structural overlay and reconstruction thicknesses are known, joint spacing recommendations can be made. AIRPACS longitudinal and transverse joint spacing recommendations are based on the factors shown in DTS VI. For all AC overlays, longitudinal and transverse joints are sawed and sealed, and matched with the existing JPCP joints. Joints of a JPCP bonded overlay must also match the existing JPC layer joints, but JPCP unbonded overlay joints do not have to match the existing joints.

FIGURE 3-12 [6]
CHART FOR DETERMINING C_b FOR AC OVERLAYS

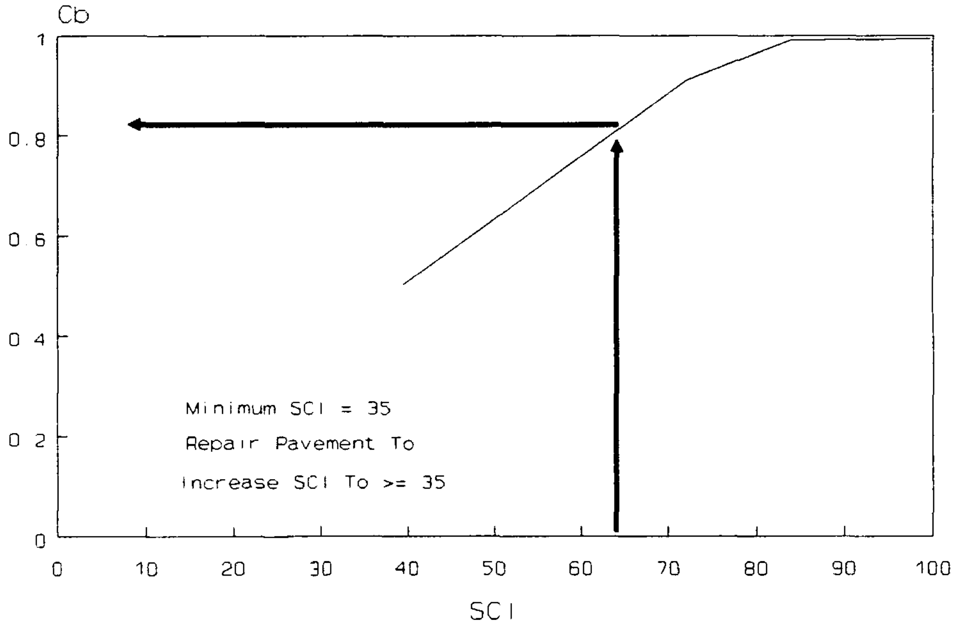
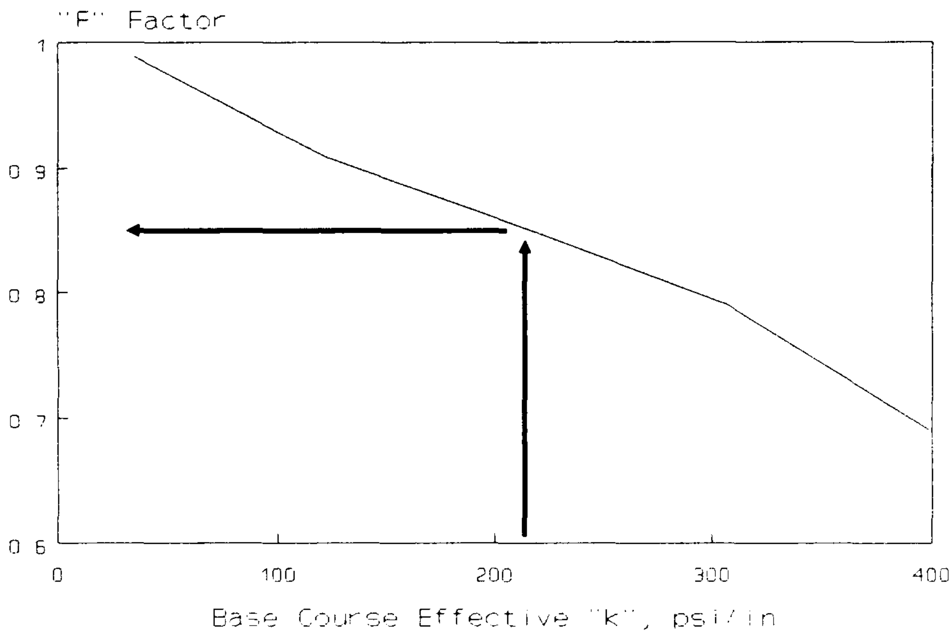


FIGURE 3-13 [6]
CHART FOR DETERMINING THE "F" FACTOR FOR AC OVERLAYS



DECISION TREE SUMMARY VI
JOINT SPACING RECOMMENDATIONS

TREE NODE	PATH DISCRIMINATORS
AC Overlay?	Yes
	No
For A JPCP Bonded Overlay, Will The Spacing Be Within 10 Percent Of the Allowable Joint Spacing?	Yes
	No
Bonded JPCP Overlay?	Yes
	No
Is Reconstruction Feasible?	Yes
	No
Section Location	Full Facility Width
	Edge OR Keel
Stabilized Base Or Subgrade?	Yes
	No
New Longitudinal Joint Spacing?	> 20 ft
	<= 20 ft

CONCLUSIONS
C1. Use Joint Spacing of 4ℓ.
C2. Use Joint Spacing of 5ℓ.
C3. Saw And Seal Joints To Match Existing Transverse And Longitudinal Joints.
C4. Use Existing Joint Spacing For Transverse And Longitudinal Joints.
C5. Bonded JPCP Overlay Is No Longer Feasible.
C6. Use/Do Not Use Longitudinal Construction Joints.

Allowable joint spacings of 4ℓ for bound material and 5ℓ for unbound material are used in the Designer knowledge-base. Joint spacings of 4ℓ are used if a new pavement layer is placed on a stabilized base or stabilized subgrade, or if an unbonded overlay is constructed on the existing JPCP. The ℓ value for unbonded overlays is calculated using the unbonded overlay thickness and a "k" value of 200 psi/in.

Joints for a bonded PCC overlay must match the existing joints. The designer DPDM computes the allowable joint spacing for a bonded overlay using the radius of relative stiffness, ℓ, that will exist after the bonded overlay is placed. For some pavements, the existing joint spacing may be too great, even after a bonded overlay is placed. If the joint spacing is so great that the existing JPCP shows cracking which has been caused by high curling and warping stresses, an expert may not recommend a bonded overlay. For practicality reasons, AIRPACS tolerates a 10 percent difference of the allowable joint spacing for bonded overlays to make it possible to match existing JPCP joints. If the existing JPCP joint spacing in either direction is 10 percent greater than the allowable joint spacing, a bonded JPCP overlay becomes infeasible. For this situation, it is better to consider an unbonded overlay than a bonded overlay where the warping and curling stresses will remain unacceptabl

The final joint spacing decision made by the AIRPACS designer is whether longitudinal contraction joints should be permitted. This recommendation is based on the joint spacing that is selected for reconstruction and overlay. If the joint spacing is greater than 20 feet, longitudinal contraction joints are not permitted. In this situation the paving lane width would be greater than 40 feet and in the past, U.S. Air Force pavements that were constructed using wide lane widths have not performed well. Consequently, most MAJCOM pavement engineers prefer not to use paving lane widths greater than 40 feet.

Once overlay thicknesses and joint spacings are known, the user will want to know how each of the surviving rehabilitation alternatives will perform. This knowledge in AIRPACS has been included in the forecaster knowledge-base. The forecaster has been identified as a separate player in the design process, but in reality, the forecaster responsibilities would probably be the responsibility of the designer. However, since the forecaster work in AIRPACS is not normally conducted in project design, this player has been identified in the design process to highlight the unique contribution of this work in the rehabilitation design process.

3.2.5 Forecaster

The Forecaster measures pavement performance by computing the area under a PCI versus time curve. The Forecaster knowledge-base computes this performance curve area using Equation 3.12. Nonlinear regression techniques were used in this equation to develop a model that would predict the PCI of the original JPCP pavement, considering any structural or safety enhancing overlay that has been constructed. Most of the information that the Forecaster needs is available from the work results of the Designer knowledge-base.

Inspection of Equations 3.12, 3.13 and 3.14 shows that the most labor-intensive tasks of computing the PCI is the computation of the various fatigue damage factors in this equation. In order to complete its work tasks, the designer must gather aircraft traffic information and compute the free edge stress for each aircraft using the pavement facility. The PCI prediction model uses the free edge stress of the original JPCP in the calculation of the DAMAGE, FATAGE and DAMCOL factors [35]. If the original JPCP is overlaid, the edge stresses are calculated with and without the overlay to compute DAMAGE and DAMCOL respectively.

If an overlay alternative is being evaluated by the Forecaster DPDM, DAMAGE will always be determined using the free edge stress associated with the NSL JPCP thickness computed by the designer. When the COE's empirical overlay equation for an unbonded JPCP has been abandoned by the designer, the Forecaster will treat the pavement as a new pavement rather than an overlaid pavement. For all other overlay scenarios, the Forecaster must compute the free edge stress for the existing JPCP without an overlay since the Designer DPDM does not retain this data. This is a trivial task since only one free edge stress calculation is required for the existing JPCP to compute fatigue damage factors.

Using this procedure to compute the edge stresses will lead to equal stresses for most types of structural overlays. Edge stresses will vary, however, between different types of safety overlays, and between safety and structural overlays. Even though edge stresses may be equal, THICK is a variable in the model that will differentiate pavement performance among the alternatives being considered.

The benefit or performance (PCI curve area) of various levels of maintenance and localized repairs must also be computed so all rehabilitation options can be compared. This is the most labor-intensive task facing the Forecaster since the existing JPCP PCI must be recomputed to account for the consequences of various repairs. Performing a repair can change the PCI by reducing the number of distresses with deducts greater than 5 points, changing the severity of the distress that is repaired, eliminating a distress, creating another type of distress (i.e. patch) or changing the quantity of a distress repaired.

Once the PCI is revised to reflect the consequences of repairs, the PCI model (Equation 3.12) can be used to predict the performance of various repair options such as restoration, emergency maintenance, critical maintenance and routine maintenance. For this rehabilitation work, the Forecaster will not be attempting to predict pavement performance for a series of different repairs. AIRPACS is only attempting to predict performance for each project being considered by the user. Since this is the case, all overlays will have an initial PCI of 100.

The benefit of all other rehabilitation options is considered by increasing the PCI based on the consequence of an option. For the various types of maintenance, the consequence (PCI "bump") of that action will be repeatedly used to increase the PCI when it falls below "trigger" values for runways, taxiways and aprons throughout the design period. Thus, the performance for each alternative is the area under the curve measured from the present to the end of the user-specified design life.

3.2.6 Economist

The economist will compute the EUAC for all options for the user-specified design life. Economist work results will complement the Forecaster's work and help the user select the alternatives which will maximize pavement performance while considering the project cost. The economist's work is straightforward and does not differ from the tradition economic analysis. Since this work is not domain specific, no explanation will be given for the use of the tools (Equations 3.15 and 3.16) used in the JPCP rehabilitation design process.

3.2.7 Budget Analyst

The final player in the rehabilitation design process is the budget analyst. No knowledge has been acquired for this player since the knowledge-base is unique for each agency that might use AIRPACS. The envisioned role of the budget analyst in AIRPACS is to provide funding guidelines when the project cost exceeds the current budget. Pavement engineers hope that a project will be selected because it will enhance JPCP performance more than any other alternative. Unfortunately, budget constraints may be the overriding factor in selection of the preferred alternative.

However, many agencies may fund a project if the cost is close to the budget. Budget range and target information could be represented in the budget analyst knowledge-base. In addition, agency procedures for obtaining approval for an increase in the current budget could also be included in this knowledge-base. This type of policy information in AIRPACS would increase the chances of funding for the preferred rehabilitation design.

This discussion illustrates the diversity of the types of knowledge used in the JPCP rehabilitation decision process. The next chapter discusses how the various types of knowledge acquired during this research were represented in AIRPACS using a Blackboard architecture and the Goldworks II expert system tool.

CHAPTER 4

FUNCTIONAL DESCRIPTION OF AIRPACS

This chapter discusses how the knowledge in Chapter 3 is represented in AIRPACS to solve rehabilitation design problems for airport jointed plain concrete pavements. The knowledge engineering techniques and methods used in AIRPACS focus on a natural representation of the airport pavement system and a transparent representation of the problem solving knowledge used by participants in the rehabilitation design process. AIRPACS solves design problems using a Blackboard architecture which is similar to the Crossword Blackboard architecture discussed in Chapter 2.

4.1 OVERVIEW OF AIRPACS

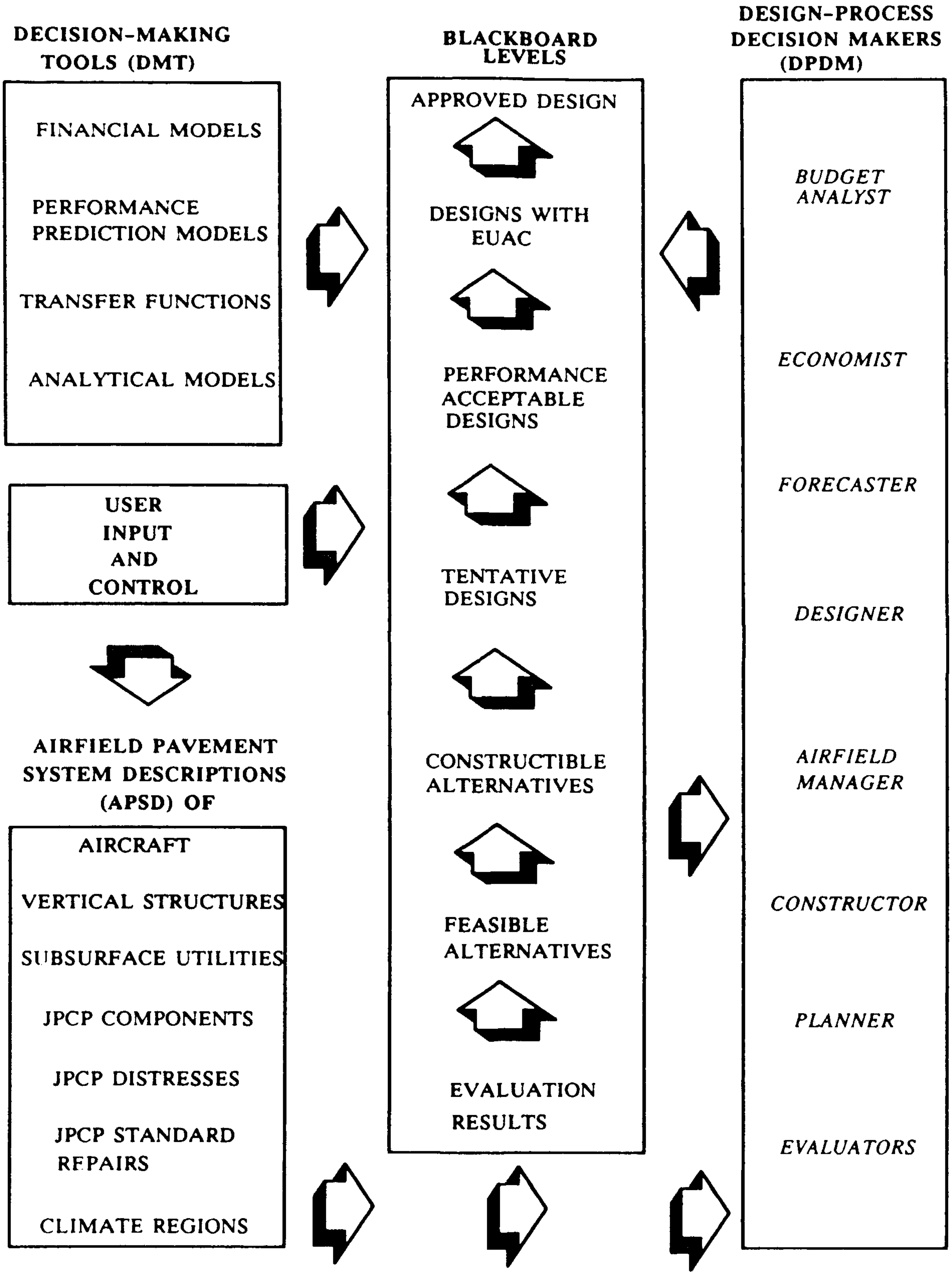
Figure 4-1 shows the Blackboard architecture that is used in AIRPACS. The knowledge-bases include decision-making tools (DMT), the airfield pavement system descriptions (APSD) and the design-process decision makers (DPDM). The design process begins with the **Evaluation-Results** level on the Blackboard and proceeds to the **Approved-Design** level.

Before the design continues to the next level on the Blackboard, the KBES user must approve this move and provide key pieces of information that DPDMs need on the next level. In addition to the information posted on the Blackboard, the user also enters data which describes the airport pavement system descriptions (APSD). Finally, the user must input all evaluation results since AIRPACS currently does not include Evaluator DPDMs.

Evaluation knowledge-bases should be added to AIRPACS in the future because they will significantly enhance the capability of the KBES. Each of the evaluation DPDMs will have to use the APSD and the DMT to decide what tests to conduct, establish the scope of test work, review the test results and make recommendations which will then be used by the Planner and Designer DPDMs. At the present time, the user must directly post evaluation recommendations on the Blackboard.

The actual rehabilitation design work in AIRPACS is performed by the "Doer" and "Critic" DPDMs. "Doers" are those DPDMs in Figure 4-1 who place work results on the Blackboard that expand or provide additional insight in the design process. "Critics" are those DPDMs that identify which repair alternatives on

FIGURE 4-1
AIRPACS ARCHITECTURE



the Blackboard are not acceptable. If a repair is not acceptable, the "Critic" deletes that repair from the Blackboard. AIRPACS "Doers" include the Planner, Designer, Forecaster and the Economist, while the Constructor, Airfield-Manager and the Budget-Analyst are classified as "Critics." Each of these knowledge-bases is represented using a collection of rules.

One of the sources of information that a DPDM uses to perform its work tasks is the APSD knowledge-base. This knowledge-base consists of physical and abstract classes of airfield objects that have been naturally represented so each DPDM can easily locate APSD information and complete its work tasks. A natural representation is desirable because it is the way experts typically think about much of their knowledge and it provides a concise structural representation of useful object relationships in the airport environment [24]. Class objects which form the APSD structure are permanently stored in AIRPACS, but the user must enter data in the form of object instances to describe a specific airport.

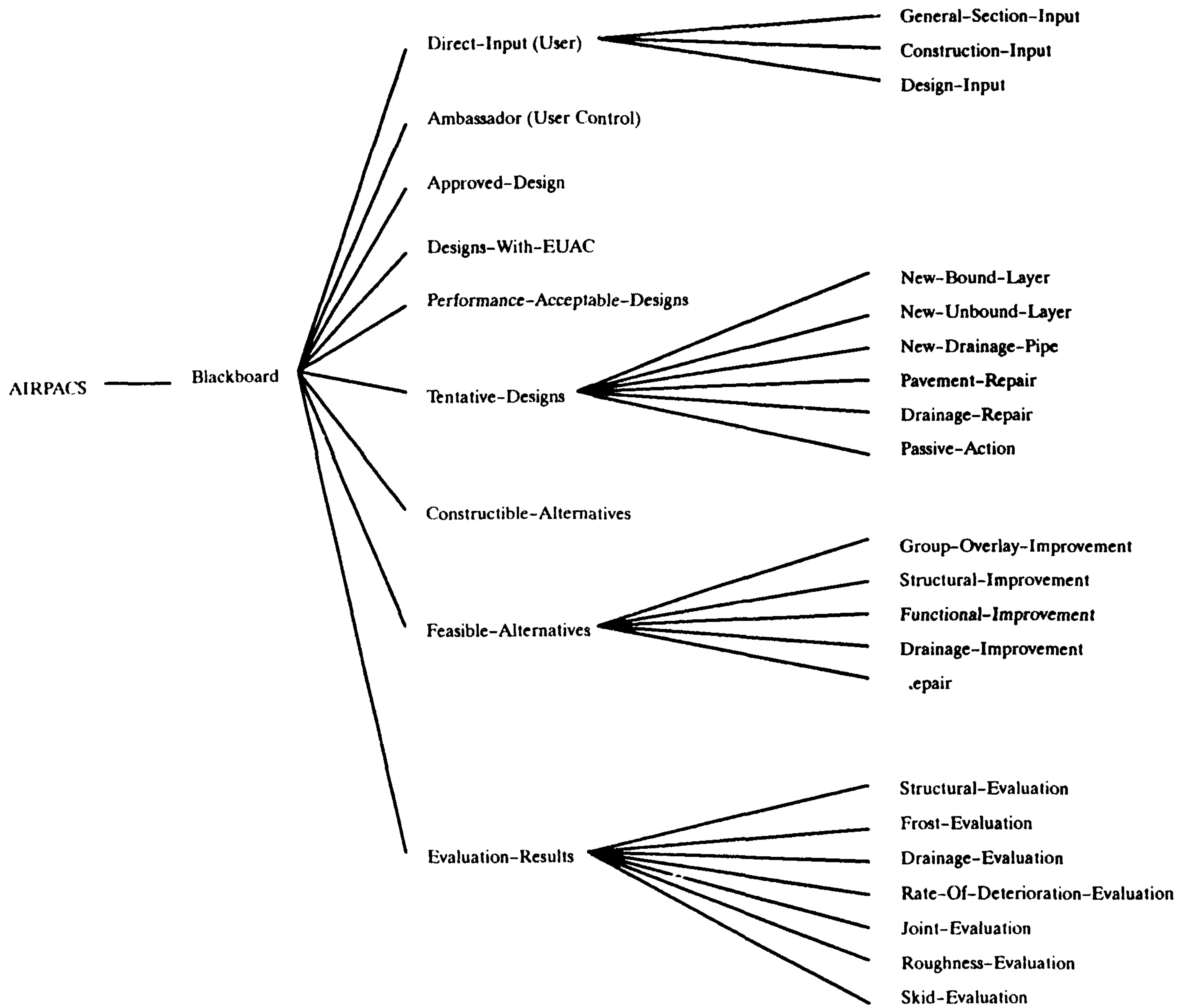
If a DPDM needs a tool to complete its work, it must send a message to the DMT knowledge-base. Messages may contain model input values as well as instructions on where to place the model output values. Capabilities and characteristics of the tools in the DMT knowledge-base were described in section 3.1. As the DPDMs work, they place design results on the appropriate level of the AIRPACS Blackboard in the form of object instances.

4.2 BLACKBOARD

Before discussing the knowledge-bases in detail, the following section will focus on how design output is represented from the lowest to highest level on the Blackboard. Each level on the Blackboard represents a subgoal that has been achieved in the rehabilitation design. **Evaluation-Results** is the lowest level while the highest level is the final design product, the **Approved-Design** (Figure 4-1).

Collections of objects are used to represent each design level and rehabilitation alternative on the Blackboard as shown in Figure 4-2. As an alternative moves to a higher level, justification and design information are carried with the alternative object. This information is carried to higher levels in the design process to minimize data dispersal on the Blackboard, making

FIGURE 4-2
BLACKBOARD CLASS HIERARCHY



it easier for a DPDM to find pertinent information about an alternative. This method of representation has the added advantage of efficiently "cleaning" the Blackboard of work data that is no longer needed after an alternative is deleted from the design process.

The lowest level on the Blackboard is the **Evaluation-Results** level which contains the results of all JPCP evaluation work shown in Figure 4-2. Since JPCP evaluation knowledge-bases are not included in this research, the user must enter the evaluation results before the design process begins. Each of the evaluation results are represented as class objects on this level. An example of the type of data that must be entered is illustrated by the **Joint-Evaluation** class shown in Figure 4-3. If a pavement section had a "T18A" designation, the instance name for this class object would be T18A-Joint-Evaluation.

On the **Feasible-Alternatives** level on the Blackboard, the Planner DPDM decides which potential rehabilitation alternatives are feasible for the current state of the pavement. Figure 4-4 shows a typical class object which represents potential structural improvements for a pavement section. If the planner is unable to make a decision about an alternative, the repair status is classified as "undetermined." All potential alternatives on this level are slots of one of the five class objects shown in Figure 4-2. In addition to "alternative" slots, these objects contain additional slots with statements that support actions taken by the Planner (Figure 4-4). These statements justify the Planner's decisions and contain information that helps other participants in the design process complete their work tasks.

The scope of work for group overlay improvements includes multiple sections on a pavement facility but the rest of the class objects on the **Feasible-Alternatives** level refer to a single JPCP section. Since each section on an airfield has a unique designation, this designation is used to create multiple instances of a class object. For example, T18A-Structural-Improvement would be the instance name of the **Structural-Improvement** class for section "T18A." If a group overlay is being considered, the KBES user must identify unique designations for each of the section groups being considered. This method of identifying feasible repairs for a section is what gives AIRPACS the capability to perform multiple rehabilitation designs for several sections.

FIGURE 4-3
CLASS OBJECT ON BLACKBOARD EVALUATION-RESULTS LEVEL

SLOTS	CONSTRAINTS	DEFAULT VALUE
Evaluation-For	Instance of Section	
Joint-Shape-Factor	Unacceptable, Marginal OR Satisfactory	Satisfactory
Load-Transfer-Distresses	Dowel-Lock-Up, Keyway-Failure OR Joint-Separation	
Winter-Trans-LTE	Number	
Spring-Trans-LTE	"	
Summer-Trans-LTE	"	
Fall-Trans-LTE	"	

JOINT-EVALUATION

When the Planner identifies a feasible option, alternative object instances are created using the slot names of the children of the **Feasible-Alternatives** class. Children are lower-class objects that inherit all attributes of higher-level classes (i.e., parents). For example, if the Planner approves an unbonded JPCP structural overlay for section T18A, the <u>T18A-JPCP-Unbonded-Struct-Overlay</u> object would become an instance of the **Constructible-Alternatives** level on the Blackboard. The **Constructible-Alternatives** object is the only class on this level and has the characteristics shown in Figure 4-5.

Besides the Planner statements, two other slots have been added to this object to represent statements made by the Airfield-Manager and the Constructor. Additional slots, such as "alternative-name," "alternative-type" and "alternative-function," of the **Constructible-Alternatives** class help the Airfield-Manager and the Constructor make decisions about the constructibility of one rehabilitation alternative or one rehabilitation category for all sections. After both DPDMs have reviewed all alternatives on this level of the Blackboard, all options that have been approved move onto the **Tentative-Designs** level. Throughout the remainder of the design process, each surviving alternative maintains its identity (i.e., instance name) as it moves from the **Constructible-Alternatives** level to the highest level on the Blackboard, the **Approved-Design** level.

FIGURE 4-4
CLASS OBJECT ON BLACKBOARD FEASIBLE-ALTERNATIVES LEVEL

SLOTS	CONSTRAINTS	DEFAULT VALUE
Improvements-For	Instance of Section	
Do-Nothing	Infeasible OR Feasible	Feasible
Limit-Aircraft-Traffic	Undetermined, Infeasible OR Feasible	Undetermined
Standard-Reconstruction	"	"
Recycle-Reconstruction	"	"
Crack-And-Seat-Reconstruction	"	"
JPCP-Bonded-Struct-Overlay	"	"
JPCP-Unbonded-Struct-Overlay	"	"
Asphalt-Structural-Overlay	"	"
Section-Keel-Replacement	"	"
JPCP-Thickness-Too-Thin		
JPCP-Thickness-Adequate		
Planner-Mission-Statement	(Multiple Values Are Allowed)	
Planner-Visual-Observation	"	
Planner-Fatigue-Statement	"	
Planner-Surface-Statement	"	
Planner-Pavement-System-Statement	"	

STRUCTURAL-IMPROVEMENT

If a rehabilitation object makes it to the **Tentative-Designs** level, it becomes an object instance of one of the object classes shown in Figure 4-2. This research focused on the design of all instances of the **New-Bound-Layer**, **Pavement-Repair** and **Passive-Action** classes. As was previously mentioned, this research does not include drainage or frost protection design which is the majority of the work required for the **New-Unbound-Layer**, **New-Drainage-Pipe** and **Drainage-Repair** classes.

All child classes of the **Tentative-Designs** level have all the slots shown in Figure 4-5 plus a "designer-statement" slot. In addition, each child class has several other slots which describe an alternative's design characteristics. Figure 4-6 shows the additional slots that are added for the **New-Bound-Layer** class. The "aircraft and-free-edge-stress" slot is a list of all aircraft that use a pavement section and the transverse free edge stress that each

FIGURE 4-5
CLASS OBJECT ON BLACKBOARD CONSTRUCTIBLE-ALTERNATIVES LEVEL

SLOTS	CONSTRAINTS
Alternative-Name	Lisp Symbol
Alternative-Type	Drainage, Reconstruction, Overlay, Repair, Traffic-Change OR Do-Nothing
Alternative-Function	Increase-Aircraft-Payload OR Improve-Aircraft-Safety
Design-Section	Instance of Section
Group-Overlay-Members	(Multiple Values Are Allowed)
Project-Reconstruction-Yardage	"
Status	Constructor-Approved AND/OR Airfield-Manager-Approved (Multiple Values Are Allowed)
Planner-Mission-Statement	(Multiple Values Are Allowed)
Planner-Visual-Observation	"
Planner-Fatigue-Statement	"
Planner-Surface-Structural-Statement	"
Planner-Pavement-System-Statement	"
Planner-Surface-Functional-Statement	"
Planner-Drainage-Statement	"
Planner-Repair-Statement	"
Planner-Repair-Selection	"
Constructor-Statement	"
Airfield-Manager-Statement	"

CONSTRUCTIBLE-ALTERNATIVE

aircraft creates for a design state. "Season-design-deflection-LTE" and "stress-load-trans-eff" slots each have four load transfer efficiency values representing a typical value of each season. The SLTE values are used to determine the edge stress for each aircraft for each season. Thus, the "aircraft-and-edge-stress" slot contains lists of all using aircraft and the four seasonal stresses each aircraft creates in the JPC layer. Values in this slot and the "aircraft-and-annual-coverages" slot are used to estimate future Miner's damage for each aircraft for each season. The results are placed in the "aircraft-and-Miners-damage" slot.

FIGURE 4-6
CLASS OBJECT ON BLACKBOARD TENTATIVE-DESIGNS LEVEL

SLOTS	CONSTRAINTS
Design-Modulus-Of-Rupture	Number
Design-Modulus-Of-Elasticity	"
Design-Subgrade-k-Value	"
Radius-Of-Relative-Stiffness	"
Overlay-Radius-Of-Relative-Stiffness	"
New-Layer-Thickness	"
Overlay-Thickness	"
Aircraft-And-Free-Edge-Stress	(Multiple Values Are Allowed)
Season-Design-Deflection-LTE	
Stress-Load-Transfer-Eff	
Aircraft-And-Edge-Stress	(Multiple Values Are Allowed)
Aircraft-And-Annual-Coverages	"
Aircraft-And-Miners-Damage	"
Past-Miners-Damage	Number
Total-Miners-Damage	"
New-Layer-Long-Joint-Spacing	"
New-Layer-Trans-Joint-Spacing	"
Long-Construct-Joint-Type	Dummy-Groove, Doweled, Keyed OR Keyed-Tie-Bar
Trans-Construct-Joint-Type	"
Long-Contract-Joint-Type	None, Dummy-Groove, Dummy-Groove-Doweled OR Dummy-Groove-Tie-Bar
Trans-Contract-Joint-Type	"
Dowel-Diameter	Number
Dowel-Spacing	"
Dowel-Yield-Strength	"
Dowel-Length	"
Joint-Width	"
Joint-Depth	"
Joint-Sealant-Shape-Factor	"
Fuel-Resistant-Sealant	Yes OR No
Joint-Sealant-Type	Hot-Field-Poured, Cold-Field-Poured, OR Preformed

NEW-BOUND-LAYER

Once the thickness and joint design are complete, the alternative objects move from the **Tentative-Designs** level to the **Performance-Acceptable-Designs** level on the Blackboard. Results posted on the **Tentative-Designs** level on the Blackboard were transferred to a Lotus v3.0 1-2-3 spreadsheet for AIRPACS validation tests. Work results from both the **Performance-Acceptable-Designs** and the **Designs-With-EUAC** levels are presented in Lotus 1-2-3 spreadsheets. Decision-making tools that were described in section 3.1 are used in the spreadsheet to validate AIRPACS rehabilitation work. Validation examples in Chapter 5 illustrate how an alternative object is created and how it moves to higher levels on the Blackboard and, finally, to the Lotus spreadsheet for performance prediction and economic analysis work.

4.3 KNOWLEDGE-BASES

Participants in the design process need more than pavement evaluation results to move rehabilitation alternatives from a lower to higher solution state on the Blackboard. In addition to evaluation results, design participants need the tools discussed in section 3.1 and information about the airport to make decisions. Physical and abstract *information* are used to describe the organization and composition of an airport, while tools are used to describe the behavior of the objects in this domain. This structured model of the airport is known as the airfield pavement system description (APSD) while the behavioristic model is known as the decision-making tools (DMT).

4.3.1 Structured Model of the Airport System

Collections of objects are used to describe the relationships between those objects of the APSD that affect the decision-making of participants in the rehabilitation design process. These objects should naturally represent physical and abstract objects as they exist in an airport environment. A natural representation of the airport environment makes it easier for the knowledge engineer to write rules that are easy to understand.

One of the most important classes in the APSD is the **Section** since this object is the basis for the project scope of work. Several pavement sections may be designed together, but the rehabilitation options will always be selected and designed for a specific pavement section. Design information that relates to the pavement section includes knowing which aircraft operate on a section, what distresses exist in a section, what subsurface layers exist in a section and what pavement facility the section is a "part-of." The following discussion demonstrates how object classes are naturally represented in AIRPACS and why the "section" is the focal object in the APSD.

4.3.1.1 Physical Objects

Figure 4-7 represents the relationships between those physical class objects of the APSD that have an affect on the pavement rehabilitation design process. Each of the lines shown in this figure represents an "is-a" relationship between class objects. For example, a **Sub-Surface-Layer** is a **Subsurface-Part** and a **Pavement-Structural-Layer**, which is a **Section-Part**, etc. For this example, the **Pavement-Structural-Layer** class would inherit all attributes of the **Section-Part** parent class and all of its parent's attributes.

Many of the class objects shown in Figure 4-7 have slots or attributes that identify a relationship between one or more object instances. Each of these slots must have a slot value that is an instance of a specific class. For example, assume T18A is an object instance of the **Section** class and North-South-Taxiway is an object instance of the **Pavement-Facility** class. If rehabilitation options are being designed for T18A and pavement facility information is required, AIRPACS must first find which pavement facility T18A is a "part-of." Since the "part-of" slot of the T18A object contains the slot value North-South-Taxiway, AIRPACS knows that pavement facility data about the North-South-Taxiway object should be used in the design.

One of the key interactions in the airport environment occurs between the JPCP and operational aircraft. Figures 4-8 and 4-9 show the slots of aircraft classes that describe aircraft and identify which pavement sections the aircraft use. The "operates-on-section" and "future-average-annual-passes" slots of the **Aircraft** class identify how frequently each aircraft model uses a pavement section. Each aircraft model is represented as an instance in the airfield pavement system description (APSD) in AIRPACS. Since different aircraft models may have very similar main gears, the "part-of" slot of one instance of the **Landing-Gear** class may contain several aircraft instances. For example, the "AC-130H," "EC-130E," "HC-130N" and "HC-130P" aircraft instances all have main gears with similar characteristics; therefore, only one main-gear instance exists in AIRPACS for these aircraft.

FIGURE 4-7
APSD PHYSICAL CLASS HIERARCHY

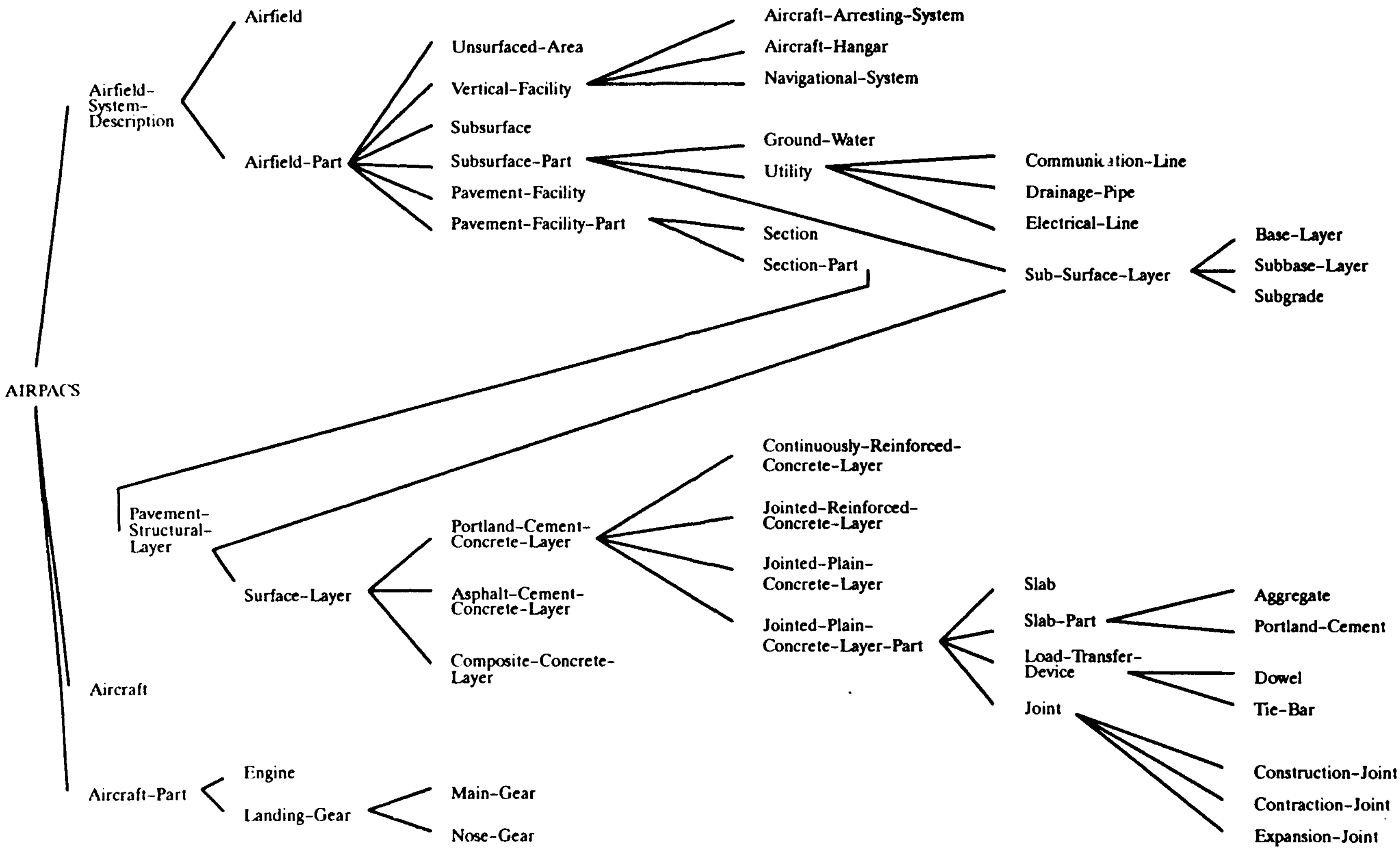


FIGURE 4-8
AIRCRAFT CLASS OF THE APSD

SLOTS	CONSTRAINTS	DEFAULT VALUE
Parts	(Multiple Values Are Allowed)	Nose-Gear, Main-Gear, Engine
Operates-On-Section	Instance of Section	
Aircraft-Type	Cargo, Passenger, Fighter, Bomber, Tanker OR Special	
Aircraft-Group-Index	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 OR 13	
Aircraft-Group-Category	Light, Medium OR Heavy	
Number-Of-Engines	Number	2
Number-Of-Main-Gear-Pairs	"	2
Future-Average-Annual-Passes	"	

AIRCRAFT

FIGURE 4-9
LANDING-GEAR CLASS OF THE APSD

SLOTS	CONSTRAINTS
Part-Of	Instance Of Aircraft
Runway-Coverage-Ratio	Number
Taxiway-Coverage-Ratio	"
Tire-Load	"
Tire-Contact-Area	"
Equivalent-Radius-Eqn-Coef	(Multiple Values Are Allowed)
Gear-Load	Number
Tire-Radius	"
Tire-Pressure	"
Tire-Spacing-X-Direction	"
Tire-Spacing-Y-Direction	"

LANDING-GEAR

The aircraft and gear instances in AIRPACS are based on the FAA, U.S. Air Force and Asphalt Institute aircraft characteristics manuals [17, 69, 70, 71]. Most of the data in these instances do not have to be changed by the KBES user. However, the "operates-on-section" slot values will always have to be input by the user. In addition, the user has the option of modifying "tire-load" and "gear-load" slot values to represent the specific loading condition of the operational aircraft at an airport.

The preceding discussion illustrates how the airport environment has been represented to help the DPDMs quickly find airport data in the hierarchy of objects that describe this environment. For all of these physical objects, the logical connection between objects has been described using "is-a" relationships between classes and instance slot values. The following section introduces abstract objects in the airport that do not have "is-a" and "part-of" relationships with the physical objects. However, class slots can be used to describe other types of relationships that exist between physical and abstract classes in the APSD.

4.3.1.2 Abstract Objects

Besides the physical objects of the airport system, there are abstract classes that describe relationships between all objects of the APSD knowledge-base. Airfield pavement distresses, distress repairs and climatic regions are abstract classes found in AIRPACS as shown in Figure 4-10. These classes complement the physical classes and make it possible for the design-process decision makers to select and design rehabilitation options. An explanation of the abstract classes will complete the discussion of the APSD knowledge-base.

All JPCP distresses shown in Figure 4-10 were discussed in section 3.1.1 and represent all distresses recorded during a PCI survey. This information is critical to successful selection and design of rehabilitation alternatives. Even if a PCI survey has not been completed, the KBES user should estimate the distress quantities for a pavement section. Otherwise, AIRPACS will produce successful results for a limited number of design scenarios.

A typical class for a "severity-level" JPCP distress is shown in Figure 4-11. The slots shown in these figures include those slots inherited from the

FIGURE 4-10
APSD ABSTRACT CLASS AND INSTANCE HIERARCHY

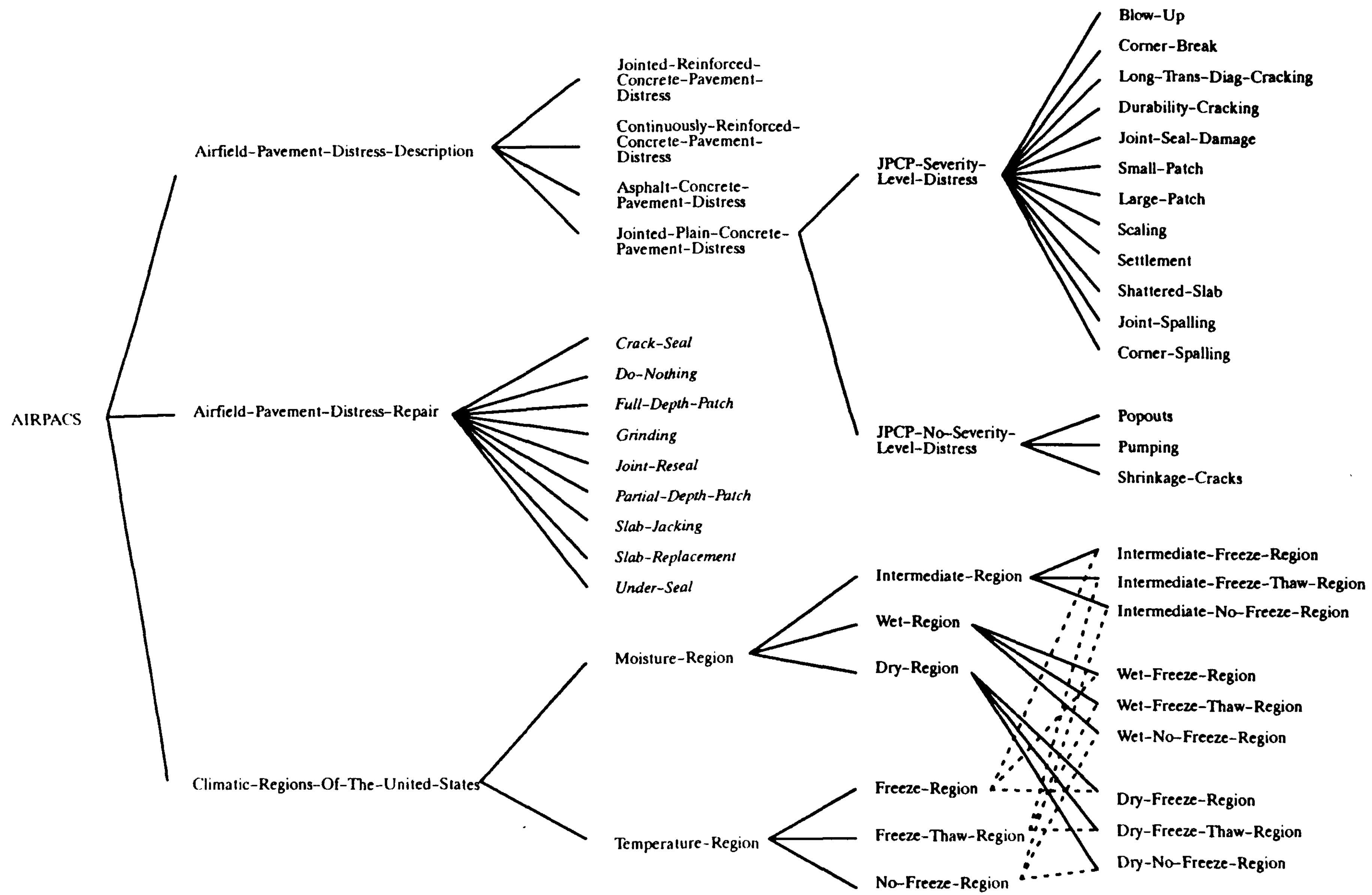


FIGURE 4-11
JPCP-SEVERITY-LEVEL-DISTRESS CLASS OF THE APSD

SLOTS	CONSTRAINTS	"WHEN-MODIFIED" DAEMONS	DEFAULT VALUE
Distress-Of-Section	Instance-Of-Section		
Abbrev-Name			LTDC
Low-Severity-Quantity	Value Between 0 & 100	Calculate-Severity-Deduct Pass-Cracked-Slabs Update-Quantity-Total	0
Low-Severity-Deduct		Pass-PCI-Deduct	0
Low-Severity-Coef			-1.15 3.92 0.325
Medium-Severity-Quantity	Value Between 0 & 100	Calculate-Severity-Deduct Pass-Cracked-Slabs Update-Quantity-Total	0
Medium-Severity-Deduct		Pass-PCI-Deduct	0
Medium-Severity-Coef			0.108 3.11 2.09
High-Severity-Quantity	Value Between 0 & 100	Calculate-Severity-Deduct Pass-Cracked-Slabs Update-Quantity-Total	0
High-Severity-Deduct		Pass-PCI-Deduct	0
High-Severity-Coef			0.164 3.55 3.27
Total-Quantity			0

LONG-TRANS-DIAG-CRACKING

parent classes shown in Figure 4-10. A short example will illustrate the behavior of an instance of the class shown in Figure 4-11. Assume that 15 percent of the slabs in section T18A have low-severity cracking. AIRPACS would create the instance T18A-LTD-Cracking once the user indicates this distress exists. When the user enters the quantity 15 in the "low-severity-quantity" slot of T18A-LTD-Cracking, a series of actions are taken by "when-modified" daemons.

The first daemon calculates the PCI deduct value for longitudinal-transverse-diagonal cracking using regression equations that were developed in this research. These equations estimate the deduct using the deduct curves found in several PCI survey manuals [31, 32]. After the daemon calculates a deduct value of 11.85, it places this value in the "low-severity-deduct" slot of T18A-LTD-Cracking. At this time, two other daemons are activated. One daemon passes this deduct to the "distress-deducts" slot of the T18A section instance. The second daemon passes the distress quantity to the "percent-slabs-cracked" slot of the T18A instance. The last daemon activated of the T18A-LTD-Cracking instance adds 15 to the current value in the "total-quantity" slot.

Daemon activity of the T18A-LTD-Cracking instance also initiates daemon activity in the T18A instance. When the deduct is placed in the "distress-deducts" slot of the latter instance, the daemon reviews the distress type. For this example, it will place the deduct value in the "deducts-PCI" and "deducts-SCI" slots, but not the "deducts-FCI" slot of the T18A pavement section. This sequence of daemon activity is repeated each time the KBES user enters another distress quantity.

Standard repairs for each of these JPCP distress classes are represented as instances of the **Airfield-Pavement-Distress-Repair** class. Instances of this class are shown in italics in Figure 4-10. The instances reflect the repair guidance that was presented in Table 3-3. For example, crack sealing will improve pavement performance if it is used for those distresses shown in Figure 4-12. Not shown in this figure are those distresses that should not be repaired using crack sealing. Default values of "not-applicable" apply for these distresses. A "no-severity" slot value is used for pumping since this distress has no severity level.

An essential component of the airfield description is a description of the climatic regions in the United States. The KBES user selects the moisture and temperature regions for the airport location using the regions shown in Figures 3-5 and 4-10. With this information, AIRPACS will create an instance of the appropriate region and enter the airport name in the "airfield" slot. If the airport is located in the wet-freeze-thaw-region, the corresponding class will have the slots shown in Figure 4-13, which includes all slots inherited from parent classes.

The abstract areas of the APSD have many types of relationships with the physical objects of the APSD. Figures 4-11 through 4-13 illustrate some of the relationships that exist between the physical and abstract descriptions of the airfield. These figures also illustrate the dynamic activity that occurs within the APSD as the user enters airfield data which triggers daemon activity.

FIGURE 4-12
CRACK-SEAL INSTANCE OF THE APSD

INSTANCE	SLOT VALUES
Pavement-Type	JPCP CRCP JRCP Asphalt
Corner-Break	Low-Severity Medium-Severity High-Severity
Long-Trans-Diag-Cracking	Low-Severity Medium-Severity High-Severity
Durability-Cracking	Low-Severity
Small-Patch	Medium-Severity
Large-Patch	Medium-Severity
Shattered-Slab	Low-Severity Medium-Severity High-Severity
Pumping	No-Severity

CRACK-SEAL

FIGURE 4-13
WET-FREEZE-THAW-REGION CLASS OF THE APSD

SLOTS	CONSTRAINTS	DEFAULT VALUE
Airfield	Instance of Airfield	
Avg-Annual-Rainfall	Number	
Moisture-Region		Wet-Region
Avg-Annual-Temperature	Number	
Mean-Daily-Winter-Temperature	"	43
Mean-Daily-Spring-Temperature	"	66
Mean-Daily-Summer-Temperature	"	79
Mean-Daily-Fall-Temperature	"	64
Temperature-Region		Freeze-Thaw-Region

WET-FREEZE-THAW-REGION

4.3.2 Behavioristic Model of the Airport System

Most of the daemon activity in AIRPACS occurs in the DMT knowledge-base which describes the behavior of the objects in the APSD. The APSD describes the physical and abstract objects in an airport environment, but another model is used to describe the behavior of objects within the airport system. With the exception of the PCI tools, all tools described in section 3.1 are part of the behavioristic model or decision-making tools (DMT) (Figure 4-1). Since the user is not allowed to modify the DMT, all classes and instances are shown in Figure 4-14.

Since no models were developed to estimate the stresses in a two-layer pavement system, a single-layer model and empirical overlay equations are used in thickness designs. When a two-layer model is developed in future research, the model can be updated as shown in Figure 4-14. At the present time, unbonded JPCP and asphalt overlay thickness design are implemented using the procedures discussed in section 3.2.4.

The following discussion illustrates how the tool classes shown in Figures 4-15 through 4-17 assist the Designer in determining stresses, joint load transfer and concrete fatigue damage. The Designer DPDM uses these models to perform thickness designs for structural overlays or reconstruction. Daemon activity begins when the Designer selects a trial JPC layer thickness and then sends a message to the Seiler-Single-Layer-Stress-Model instance of the **Single-Layer-Stress-Model** class. This message tells this model to determine the free edge stress in the slab for each aircraft that uses a JPCP section. Just before a DPDM rule sends this message, that rule places values in the "alternative," "aircraft," "aircraft-main-gear," and "gear-load" slots of the Seiler-Single-Layer-Stress-Model. When this handler accesses the "free-edge-stress" slot of this object, the "calculate-free-edge-stress" daemon is activated.

Once the "calculate-free-edge-stress" daemon is activated, it uses data from tool, alternative and aircraft instances to determine the stress. During this process, the daemon accesses the "equivalent-single-wheel-radius" slot shown in Figure 4-15 which in turn activates the "calculate-ESWR" daemon shown in this figure. After both daemons have completed their tasks, the handler places a list of the main gear, aircraft and free edge stress in the correct slot of the alternative object on the **Tentative-Design** level on the Blackboard. For example, the message might place the "(B-747-Main-Gear-1 B-747 567)" value in the

FIGURE 4-14
DMT CLASS HIERARCHY

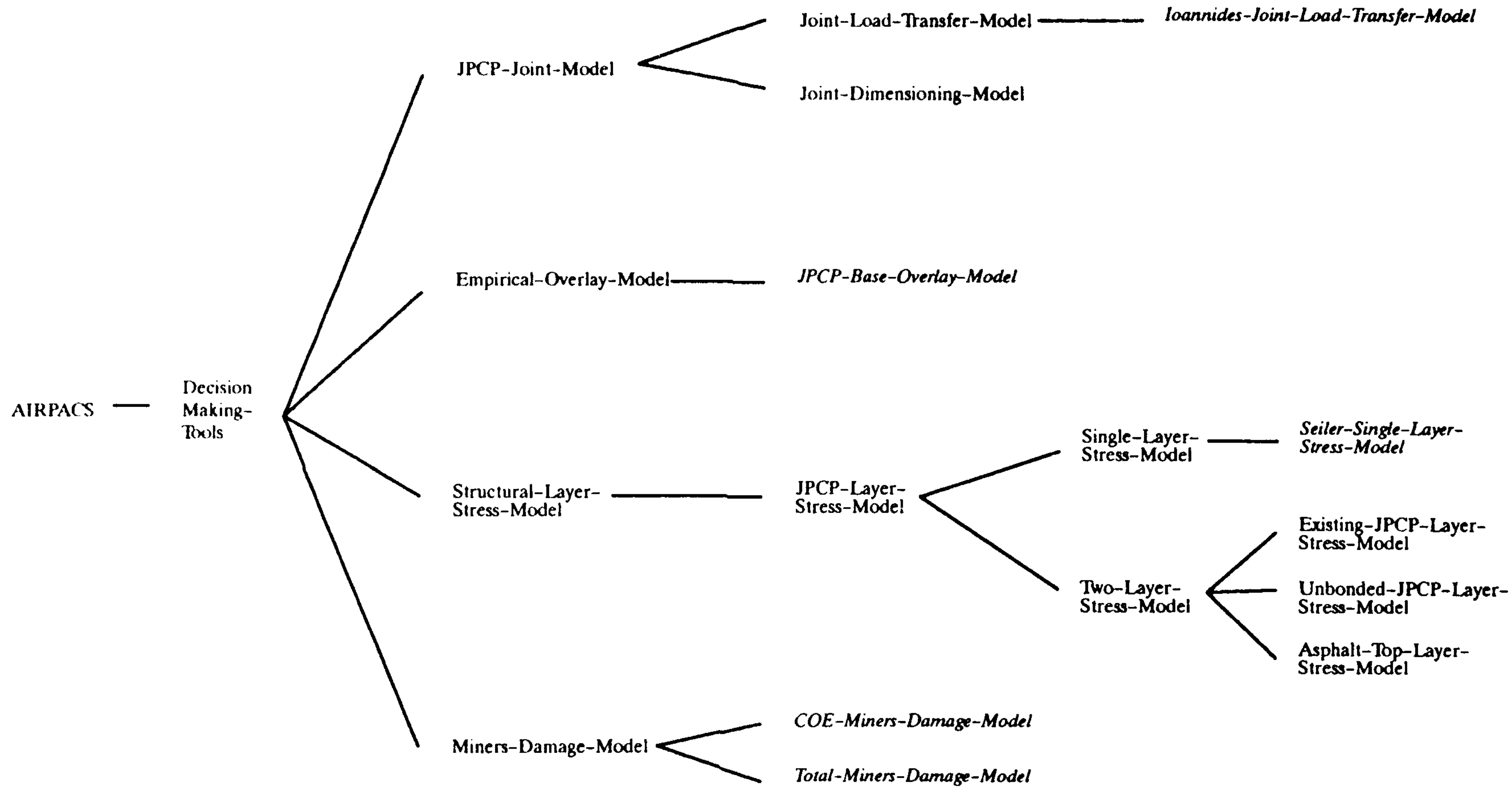


FIGURE 4-15
SINGLE-LAYER-STRESS-MODEL CLASS OF THE DMT

SLOTS	CONSTRAINTS	"WHEN-ACCESSED" DAEMONS
Alternative		
Aircraft	Instance Of Aircraft	
Aircraft-Main-Gear	Instance Of Main-Gear	
Gear-Load	Number	
Equivalent-Single-Wheel-Radius		Calculate-ESWR
Free-Edge-Stress		Calculate-Free-Edge-Stress

SINGLE-LAYER-STRESS-MODEL

"aircraft-and-free-edge-stress" slot of the T18A-JPCP-Bonded-Struct-Overlay instance of the **New-Bound-Layer** class on the Blackboard. These actions complete steps 3 through 5 of Figure 3-10, "Single Layer JPCP Thickness Design Procedure."

The next message is sent from the Designer DPDM to the Ioannides-Joint-Load-Transfer-Model instance and tells this object to calculate the edge stress for each season for an aircraft. Figure 4-16 shows that the "calculate-stress-LTE" daemon is activated when the message handler accesses the "season-design-stresses" slot. But before this daemon can complete its work, it must activate an additional daemon.

The "calculate-ESWR-over-stiffness" daemon calculates the ESWR/ℓ (a/ℓ) ratio which is used to determine the SLTE (Figure 3-2). When this daemon completes its work, the "calculate-stress-LTE" daemon resumes work. It determines the stress load transfer efficiency for each season by using the ESWR/ℓ ratio, the four season DLTE values already posted on the Blackboard and the DLTE vs. SLTE relationhsips shown in Figure 3-2. The "calculate-ESWR-over-stiffness" and "calculate-stress-LTE" daemons are located in the slots shown in Figure 4-16.

When these daemons have completed their work, the "calculate-season-stresses" daemon is immediately activated since it now has sufficient data to complete its work. This daemon uses the four SLTE values to compute the seasonal transverse edge stresses for the current trial JPC layer thickness. After the daemon completes this work, the "find-edge-stress" message handler resumes it work and places the main gear, aircraft and seasonal edge stresses in the correct

FIGURE 4-16
JOINT-LOAD-TRANSFER-MODEL CLASS OF THE DMT

SLOTS	CONSTRAINTS	"WHEN-ACCESSED" DAEMONS
Alternative		
Aircraft	Instance Of Aircraft	
Aircraft-Main-Gear	Instance Of Main-Gear	
Equivalent-Single-Wheel-Radius		
Free-Edge-Stress		
Stress-Load-Trans-Eff		
Season-Design-Deflection-LTE		Calculate-Season-LTE
Season-Design-Stresses		Calculate-Stress-LTE Calculate-Season-Stresses
Season-Mean-Daily-Temperatures		
ESWR-Over-Stiffness		Calculate-ESWR-Over-Stiffness
ESWR-Over-Stiffness-Coeff		

JOINT-LOAD-TRANSFER-MODEL

slot of the alternative object on the **Tentative-Design** level on the Blackboard. For example, the message might place the "(B-747-Main-Gear-1 B-747 550 540 475 510)" value in the "aircraft-and-edge-stress" slot of the T18A-JPCP-Bonded-Struct-Overlay instance of the **New-Bound-Layer** class on the Blackboard. These actions will complete steps 6 through 8 of Figure 3-10, "Single Layer JPCP Thickness Design Procedure."

The Designer DPDM then sends a message to the DMT KB telling it to find out how much an aircraft will damage the pavement in the future given the current trial thickness of the PCC layer. This message is sent to the COE-Miners-Damage-Model instance of the **Miners-Damage-Model** class shown in Figure 4-17. When the "find-aircraft-Miners-damage" handler accesses the "pavement-damage-by-one-aircraft" slot in this figure, the "calculate-pavement-damage" daemon is activated. This daemon assumes that the aircraft annual traffic is uniformly distributed throughout the year. Using this assumption, the daemon computes the total fatigue damage by first computing seasonal damages. Next, the message places the "(B-747-Main-Gear-1 B-747 0.111)" value in the "aircraft-and-Miners-damage" slot of the T18A-JPCP-Bonded-Struct-Overlay instance of the

FIGURE 4-17
MINERS-DAMAGE-MODEL CLASS OF THE DMT

SLOTS	CONSTRAINTS	"WHEN-ACCESSED" DAEMONS
Aircraft	Instance Of Aircraft	
Aircraft-Main-Gear	Instance Of Main-Gear	
Aircraft-Characteristics		
Aircraft-Annual-Coverages		
Pavement-Damage-By-One-Aircraft		Calculate-Pavement-Damage
Total-Future-Damage		Calculate-Total-Future-Damage
Facility-Type	Lisp Symbol	
Pavement-Design-Life	Number	
Edge-Stresses-By-Season		
Design-Modulus-Of-Rupture		

MINERS-DAMAGE-MODEL

New-Bound-Layer class on the Blackboard. This action completes step 9 in Figure 3-10, "Single Layer JPCP Thickness Design Procedure."

The preceding examples illustrate how the tools in AIRPACS are used in rehabilitation design. In building construction, a foreman may tell a worker which tool to use for a construction task. In pavement design, Designer DPDMs act in a similar manner when they send a message to the DMT knowledge-base and tell this KB which tool in section 3.1 to use for the current design task. The following section discusses how the knowledge of design-process decision makers is represented using the rule-based capabilities of Goldworks II.

4.3.3 Decision-Making Knowledge

Unlike the DMT and APSD knowledge-bases, the design process decision-maker (DPDM) knowledge-bases provide design direction in the rehabilitation design process. Each DPDM consists of one or more rule sets which move a rehabilitation design to the next level on the Blackboard (Figure 4-1), thereby achieving one subgoal in the overall design process. For each level on the Blackboard, the solution state within that level is constantly changing as the DPDM attempts to achieve the subgoal. The first subgoal of AIRPACS is to identify feasible alternatives for all pavement sections that the user wants AIRPACS to consider.

This work is completed by the Planner KB after the KBES user enters pavement evaluation results and allows the Planner to begin work.

4.3.3.1 Planner

The Planner DPDM is responsible for reviewing all airport system information and then selecting feasible rehabilitation alternatives for a JPCP. The Planner selects feasible alternatives and places justification statements on the Blackboard as described in section 4.2. Justification statements are a collection of problem-solving subgoals that have been met and are used by the Planner to solve higher-level goals (i.e. JPCP bonded overlay is infeasible). These statements justify the Planner's decision and at the same time provide key pieces of information that are used throughout the rehabilitation design process.

Rules are easier to understand when justification statements are used in the antecedents and consequences of a rule. Figure 4-18 shows three rules that are used to decide what drainage repairs may be required for a pavement section. The first rule identifies an airfield with poor natural drainage while the second rule uses this justification statement to conclude that the pavement section has unacceptable base and subgrade drainage. Finally, the third rule uses these justification statements to conclude that a permeable base is required, but cannot be installed since all reconstruction options are infeasible.

Using rule names that describe rule conclusions and keeping the size of rules small so the purpose of a rule is clearly understood are two knowledge representation objectives in AIRPACS. The rules in Figure 4-18 illustrate these objectives and are typical of rules in the Planner rule base. If Planner knowledge is represented in this manner, conclusion justification is easier to comprehend since the names of the rules that may fire describe possible conclusions. This is an important characteristic of this knowledge-base since it has the largest rule base of all the DPDMs.

Table 4-1 shows the number of rules in each rule set and the Planner actions completed by a rule set. The decision tree paths for the Planner rule base is shown in Appendix E, but the rules are only listed in Volume II of this research [68]. One of the rule sets shown in Table 4-1 is the "control" rule set which has the primary function of activating and deactivating rule sets as the Planner selects feasible alternatives. Rule sets help the Planner reach conclusions faster since the Goldworks II inference engine matches only rules

FIGURE 4-18
PLANNER RULES WITH JUSTIFICATION STATEMENTS

```
(DEFINE-RULE POOR-NATURAL-DRAINAGE
   (:PRIORITY 100)
 (INSTANCE ?SECTION-UNDER-DESIGN IS SECTION
         WITH DESIGN-STATUS PLANNING)
 (INSTANCE ?UNSURFACED-AREA IS UNSURFACED-AREA
         WITH PART-OF ?AIRFIELD
         WITH NATURAL-DRAINAGE-INDEX ?NATURAL-DRAINAGE-INDEX)
 (OR
   (EQUAL ?NATURAL-DRAINAGE-INDEX 'VERY-POORLY-DRAINED)
   (EQUAL ?NATURAL-DRAINAGE-INDEX 'POORLY-DRAINED)
   (EQUAL ?NATURAL-DRAINAGE-INDEX 'IMPERFECTLY-DRAINED)
   (EQUAL ?NATURAL-DRAINAGE-INDEX 'MODERATELY-WELL-DRAINED))
 (INSTANCE ?SECTION-DRAINAGE-IMPROVEMENT IS DRAINAGE-IMPROVEMENT
         WITH IMPROVEMENTS-FOR ?SECTION-UNDER-DESIGN)
  THEN
 (INSTANCE ?SECTION-DRAINAGE-IMPROVEMENT IS DRAINAGE-IMPROVEMENT
         WITH PLANNER-SUBSURFACE-STATEMENT
         (?AIRFIELD HAS POOR-NATURAL-DRAINAGE)))
```

```
(DEFINE-RULE BASE-AND-SUBGRADE-DRAINAGE-UNACCEPTABLE
  (:PRIORITY 100)
 (INSTANCE ?SECTION-UNDER-DESIGN IS SECTION
         WITH DESIGN-STATUS PLANNING)
 (INSTANCE ?BASE-LAYER IS BASE-LAYER
         WITH PART-OF ?SECTION-UNDER-DESIGN)
 (INSTANCE ?SECTION-DRAINAGE-EVALUATION IS DRAINAGE-EVALUATION
         WITH EVALUATION-FOR ?SECTION-UNDER-DESIGN
         WITH BASE-DRAINAGE-TIME ?BASE-DRAINAGE-TIME)
 (OR
   (EQUAL ?BASE-DRAINAGE-TIME 'UNACCEPTABLE)
   (EQUAL ?BASE-DRAINAGE-TIME 'MARGINAL))
 (INSTANCE ?SECTION-DRAINAGE-IMPROVEMENT IS DRAINAGE-IMPROVEMENT
         WITH IMPROVEMENTS-FOR ?SECTION-UNDER-DESIGN
         WITH PLANNER-SUBSURFACE-STATEMENT
         (?AIRFIELD HAS POOR-NATURAL-DRAINAGE)
         WITH PLANNER-SUBSURFACE-STATEMENT
         (?AIRFIELD HAS SIGNIFICANT MOISTURE-SOURCES))
   THEN
 (INSTANCE ?SECTION-DRAINAGE-IMPROVEMENT IS DRAINAGE-IMPROVEMENT
         WITH PLANNER-SUBSURFACE-STATEMENT
         (BASE AND SUBGRADE DRAINAGE UNACCEPTABLE)))
```

```
(DEFINE-RULE NEEDED-PERMEABLE-BASE-CANNOT-BE-INSTALLED
   (:DEPENDENCY T)
 (INSTANCE ?SECTION-UNDER-DESIGN IS SECTION
         WITH DESIGN-STATUS PLANNING)
 (INSTANCE ?SECTION-DRAINAGE-IMPROVEMENT IS DRAINAGE-IMPROVEMENT
         WITH IMPROVEMENTS-FOR ?SECTION-UNDER-DESIGN
         WITH PLANNER-SUBSURFACE-STATEMENT
         (?BASE AND SUBGRADE DRAINAGE UNACCEPTABLE))
 (INSTANCE ?SECTION-STRUCTURAL-IMPROVEMENT IS STRUCTURAL-IMPROVEMENT
         WITH IMPROVEMENTS-FOR ?SECTION-UNDER-DESIGN
         WITH PLANNER-PAVEMENT-SYSTEM-STATEMENT
         (RECONSTRUCTION IS INFEASIBLE))
   THEN
 (INSTANCE ?SECTION-DRAINAGE-IMPROVEMENT IS DRAINAGE-IMPROVEMENT
         WITH PERMEABLE-BASE-INSTALLATION INFEASIBLE))
```

TABLE 4-1
PLANNER RULE SETS

RULE SET	NUMBER OF RULES	FIGURE 3-4 ACTION
Planner-Control-Rules	19	Controls Rule Set Activation
Planner-Climate-Study	11	"A" - Climate Study
Planner-Mission-Assessment	9	"B" - Study Mission Aircraft and Pavement ROD
Planner-Functional-Assessment	27	"C" - Friction Study "D" - Roughness Study "E" - FOD Potential Study
Planner-General-Condition-Assessment	11	"F" - Assess Pavement Structural Integrity
Planner-Cracking-And-Fatigue-Assessment	12	"I" - Surface Cracks And Fatigue Comparison
Planner-General-Overlay-Assessment	11	"J" - Geometric Restrictions For Overlays
Pavement-System-Assessment	23	"K" - Pavement System Assessment
Overlay-Type-Selection	43	"L" - Select Types Of Overlays
Drainage-Repair-Selection	15	"M" - Select Drainage Options
Select-Restoration-Repairs	16	"N" - Select M&R Options

within the active rule set [4]. The benefits of rule sets increase as the number of rules in a knowledge-base increases and as the size of the APSD knowledge-base increases. For the latter, it will take more time to search the APSD knowledge-base for information needed to match rules for an airfield that has 50 pavement sections than for an airfield that has 20 sections.

The Planner DPDM must use nonmonotonic reasoning when the KBES user specifies that an entire pavement facility, or a group of pavement sections within that facility, must be included in the rehabilitation design. Nonmonotonic reasoning in AIRPACS means that assertions and justification statements must be retracted if they were based on a fact that is no longer true [4, 21, 22]. In the Planner DPDM, a pavement facility or section group overlay is considered to be feasible when at least half of the group overlay area must be overlaid. Since the Planner does not initially know if each section needs an overlay or whether an overlay can be installed, it assumes that a facility or group overlay is feasible until this assumption is proven false.

In order to use the nonmonotonic reasoning capabilities of Goldworks II, several rules in the "Planner-General-Overlay-Assessment," "Pavement-System-Assessment," and "Overlay-Type-Selection" rule sets have been identified as being

FIGURE 4-19
KEY NONMONOTONIC REASONING RULES

```
(DEFINE-RULE FEW-SECTION-OVERLAYS-SO-GROUP-SECTION-OVERLAY-INFEASIBLE
   (:PRIORITY 60)
 (INSTANCE ?SECTION-GROUP IS GROUPED-SECTION-INPUT
          WITH GROUP-DESIGN-STATUS PLANNING
          WITH GROUP-SECTIONS ?GROUP-SECTION
          WITH GROUP-AREA ?GROUP-AREA
          WITH GROUP-SECTION-OVERLAY-AREA ?OVERLAY-AREA)
 (OVERLAY-AREA-LT-HALF-GROUP-AREA ?SECTION-GROUP ?GROUP-AREA)
 (INSTANCE ?SECTION-STRUCTURAL-IMPROVEMENT IS STRUCTURAL-IMPROVEMENT
          WITH IMPROVEMENTS-FOR ?GROUP-SECTION)
 (INSTANCE ?USER-INPUT IS GENERAL-SECTION-INPUT
          WITH DESIGN-SECTION ?GROUP-SECTION)
   THEN
 (INSTANCE ?SECTION-GROUP IS GROUPED-SECTION-INPUT
          WITH GROUP-BORDER-SECTION-OVERLAYS NO
          WITH FACILITY-OVERLAY NO
          WITH GROUP-DESIGN-STATUS INACTIVE)
 (INSTANCE ?USER-INPUT IS GENERAL-SECTION-INPUT
          WITH FACILITY-OVERLAY NO)
 (INSTANCE ?SECTION-STRUCTURAL-IMPROVEMENT IS STRUCTURAL-IMPROVEMENT
          WITH PLANNER-PAVEMENT-SYSTEM-STATEMENT
               (GROUP OVERLAY ATTEMPT HAS FAILED)))
```

```
(DEFINE-RULE GROUP-OVERLAY-FAILED-SO-FALL-BACK-TO-SINGLE-SECTION-DESIGN
   (:PRIORITY 64)
 (INSTANCE ?SECTION-GROUP IS GROUPED-SECTION-INPUT
        WITH GROUP-DESIGN-STATUS INACTIVE
        WITH GROUP-SECTIONS ?GROUP-SECTION)
 (INSTANCE ?SECTION-STRUCTURAL-IMPROVEMENT IS STRUCTURAL-IMPROVEMENT
        WITH IMPROVEMENTS-FOR ?GROUP-SECTION
        WITH PLANNER-PAVEMENT-SYSTEM-STATEMENT
             (GROUP OVERLAY ATTEMPT HAS FAILED))
   THEN
 (EVALUATE (ACTIVATE-RULE-SETS :NAMES '(PLANNER-GENERAL-OVERLAY-ASSESSMENT)))
 (EVALUATE (ACTIVATE-RULE-SETS :NAMES '(PAVEMENT-SYSTEM-ASSESSMENT)))
 (EVALUATE (ACTIVATE-RULE-SETS :NAMES '(OVERLAY-TYPE-SELECTION)))
 (EVALUATE (FORWARD-CHAIN))
 (EVALUATE (DEACTIVATE-RULE-SETS :NAMES '(PLANNER-GENERAL-OVERLAY-ASSESSMENT)))
 (EVALUATE (DEACTIVATE-RULE-SETS :NAMES '(PAVEMENT-SYSTEM-ASSESSMENT)))
 (EVALUATE (DEACTIVATE-RULE-SETS :NAMES '(OVERLAY-TYPE-SELECTION))))
```

"dependent" on nonmonotonic reasoning. When the feasible pavement facility or group overlay area is less than half of the total area, the first rule shown in Figure 4-19 fires and informs the Planner that a facility or group overlay attempt has failed. When the "overlay-type-selection" rule set has finished firing, the control rule set is activated and the second rule in Figure 4-19 fires. Although all assertions and justification statements have been retracted when this rule fires, inferencing must be restarted so the correct assertions and justification statements can be made using the rule sets shown in Figure 4-19. When this occurs, overlays may not be feasible for as many pavement sections because of geometric constraints.

4.3.3.2 <u>Constructor and Airfield Manager</u>

The Constructor and Airfield Manager DPDMs are much smaller than the Planner KB so each of these DPDMs are represented using a single rule set. The Constructor DPDM consists of 23 rules while the Airfield Manager DPDM contains 17 rules [68]. Since each of these design decision-makers are Critics, the order in which each DPDM works is not important. This is true since a Critic does not add new information to the Blackboard, but only approves or deletes rehabilitation alternatives on the Blackboard.

Although it does not matter which DPDM works first, both the Constructor and Airfield Manager DPDM must approve an alternative before it moves from the **Constructible-Alternatives** level on the Blackboard to the **Tentative-Designs** level. When each of these DPDMs completes its work, a single rule within the knowledge-base places a message on the Blackboard stating that work has been completed. The KBES user then determines if AIRPACS should continue with the rehabilitation design. If the user approves further work in the design process, the solution process transitions from a primarily heuristic state to a solution process that is primarily algorithmic in nature. The first "Doer" in this phase of the design process is the Designer DPDM.

4.3.3.3 <u>Designer</u>

At the present time, the Designer DPDM performs key work associated with design of overlays and reconstruction. This work is completed using three rule sets which determine thicknesses, round off and select thicknesses that exceed the minimum allowable thickness, and then design joints. This DPDM differs from the previous DPDMs since designer knowledge is primarily "how to" knowledge instead of heuristic knowledge, which is the dominate characteristic of the Planner, Constructor and Airfield Manager DPDMs.

The goal of the first rule set is to determine the thicknesses of structural overlays and a new JPC layer when reconstruction is feasible. Rule priorities are used to control the order of rule firing in the first rule set as shown in Table 4-2. All rules with a priority of 100 gather preliminary data from the APSD knowledge-base and the Blackboard. Once this data is collected, the Designer reviews all section joints and determines what load transfer efficiencies will be used in the thickness design.

TABLE 4-2
BOUND-LAYER-THICKNESS-DESIGN RULE SET

RULE PRIORITY	RULE NAMES	DESIGN OBJECTIVE
100	Select-Aircraft-And-Aircraft-Runway-Coverages Select-Aircraft-And-Aircraft-TW-Or-Apron-Coverages	Step 1 in Figure 3-10.
	Select-Material-Properties-For-Overlays Select-Material-Properties-For-Reconstruction Change-Material-Prop-Selection-For-Unbonded-JPCP-Overlay	Step 2 in Figure 3-10.
	Abandon-COE-Unbonded-Overlay-Equation	Design as a new JPC layer.
	Evaluation-Trans-Jt-Controls-Design-LTE No-Evaluation-So-Estimate-Existing-Agg-LTE No-Evaluation-So-Estimate-Existing-Dowel-LTE Agg-Interlock-Exists-Long-Joints	Step 3 in Figure 3-10.
	Use-Existing-Thickness-For-Initial-Trial-Thickness	Step 4 in Figure 3-10.
95	User-Specified-Agg-Interlock-Controls-Thickness-Design User-Specified-Doweled-Joints-Control-Thickness-Design Some-User-Specified-Long-Agg-Interlock-Jts	Selects Controlling Joint Type.
90	Aggregate-Interlock-Controls-Thickness-Design Doweled-Joints-Control-Thickness-Design Warning-About-Long-Agg-Joints	Send message to DMT OR post DLTE values on Blackboard.
50	Perform-Free-Edge-Stress-Calculation-For-Current-Thick	Send Message to DMT. Steps 5 & 6 in Fig 3-10.
40	Perform-Edge-Stress-Calculation	Send Message to DMT. Steps 7 & 8 in Fig 3-10.
30	Perform-Miners-Damage-Calculation-For-An-Aircraft	Send Message to DMT. Step 9 in Figure 3-10.
28	Use-Miners-Analysis-For-JPCP-Bonded-Overlay-Past-Damage Use-Miners-Analysis-For-JPCP-Unbonded-Overlay-Past-Damage Miners-Analysis-Not-Available-For-JPCP-Bonded-OL-Past-Damage Miners-Analysis-Not-Available-For-JPCP-Unbonded-OL-Past-Damage	Use Percent Cracked Slabs Data When Miners Data Is Not Available.
27	Past-Miners-Damage-Indicates-Pavement-Failed	(See Note)
25	Review-Aircraft-Gear-And-Determine-Total-Miners-Damage	Send Message to DMT. Steps 10, 11 & 12 in Figure 3-10.
20	Increase-The-Current-Layer-Thickness-By-1% Increase-The-Current-Layer-Thickness-By-6% Increase-The-Current-Layer-Thickness-By-15% Decrease-The-Current-Layer-Thickness-By-1% Decrease-The-Current-Layer-Thickness-By-6% Decrease-The-Current-Layer-Thickness-By-15%	Steps 13 and 14 in Figure 3-10.
10	Determine-JPCP-Bonded-Overlay-Thickness Determine-JPCP-Unbonded-Overlay-Thickness Determine-Empirical-JPCP-Unbonded-Overlay-Thickness Determine-Empirical-Asphalt-Overlay-Thickness	Compute the overlay thickness.
1	Thickness-Design-Complete	Activates the thickness-selection rule set.

Note: Past Miner's damage is included in the design for a bonded and unbonded JPCP overlay. If Miner's damage is greater than 0.95, then extensive slab replacement is necessary and AIRPACS assumes the revised Miner's damage will be 0.50.

When joint evaluation results are available and a structural overlay is being considered, the Design DPDM uses the seasonal deflection load transfer efficiency (DLTE) values for the transverse joints. If no evaluation results are available, the Designer searches the APSD to see if the pavement section has any keyed or dummy groove joints. When these joint types do not exist, the DPDM uses DLTE values of 85 percent for all four seasons to represent a typical doweled joint DLTE (See Table 3-4). However, when one of these joint types exist, the Designer sends a message to the DMT which activates the "calculate-season-LTE" daemon. This daemon then uses temperature data from the APSD, and equation 3.5 to compute a DLTE value for each season.

If a reconstruction alternative is being designed or if the unbonded JPCP overlay is being designed as a new JPC layer, the Designer will determine the DLTE values based on the types of joints the KBES user specifies. The Designer will review the user inputs to see if any of the joints are keyed or dummy groove. Once again, if any of these joint types exist, the "calculate-season-LTE" daemon will be activated. Otherwise, a DLTE value of 85 percent will be used since all the joints are doweled.

Once this preliminary design work has been completed, the Designer begins the work that is algorithmic in nature. When all rules that have a priority higher than 50 have fired, the next rule to fire sends a message to the DMT to compute the free edge stress for the current thickness. The number of times this rule fires depends on the number of sections being designed, the number of structural overlay and reconstruction objects for each section and the number of aircraft that operate on each section. For example, if 5 pavement sections are being designed, each section has 5 structural improvement objects on the **Tentative-Design** level and 5 types of aircraft operate on each section; this rule will fire 125 times for each trial thickness. The next two rules in Table 4-2 will also fire 125 times and send messages to the DMT telling it to compute edge stresses and concrete fatigue damage.

After the cumulative Miner's damage of all aircraft have been determined for all sections, the Designer decides if this damage is acceptable. If the pavement is too thick, the Miner's damage will be low and the Designer will decrease the current trial thickness. If the pavement is too thin, the Miner's damage will be high and the Designer will increase the current trial thickness. The amount of increase or decrease depends on the amount of Miner's damage.

If this value is very low or high, the designer will change the thickness by 15 percent. On the other hand, if the value is close to the acceptable range of Miner's damage values, the Designer will change the thickness by only 1 percent. This convergence method usually leads to an acceptable design in 4 to 6 cycles.

As soon as the trial thickness is changed in the object instance slot on the Blackboard, the thickness design cycle is repeated. Figure 4-20 shows that the "new-layer-thickness" slot of the overlay or reconstruction object on the Blackboard is an antecedent condition for this rule. Since the antecedent condition changed for this rule, this rule will fire another 125 times for the example problem. For most situations, this will be the first rule to fire once the trial thickness is changed.

However, a thickness change might cause higher-priority rules to fire. If a JPCP unbonded overlay is being designed, material design properties may change, or the Corps of Engineers overlay equation may be abandoned. In each of these situations, all rules that have a priority greater than 50 will fire before the rule shown in Figure 4-20. Once the trial thicknesses for all overlay or reconstruction objects have an acceptable amount of Miner's damage, the Designer DPDM will compute the overlay thicknesses using the new single layer JPCP thickness, or, in the case of a bonded JPCP overlay, the single layer JPCP thickness.

Reconstruction or overlay thicknesses may not be greater than the minimum tolerable thickness, so the second rule set is activated to review and round-off the thicknesses. Reconstruction and unbonded JPCP overlays must be greater than 5 inches thick or the object instance will be deleted. Likewise, JPCP bonded and asphalt overlays must be greater than or equal to 3 inches or the object instance will be deleted. If these criteria are met, the respective rules round the current trial thickness up to the nearest one half inch. Once all infeasible structural objects have been deleted and acceptable design thicknesses have been rounded off, joint design is initiated with the third rule set in the Designer DPDM.

Joint types, joint spacing and dowel selection are implemented as described in section 3.2.4. In addition to the criteria described in that section, the Designer also rounds the joint spacing to the nearest "quarter-foot" if the joints do not have to match or cannot be matched with the existing joints. Joint design work is the last action that is completed by the Designer DPDM.

FIGURE 4-20
"PERFORM-FREE-EDGE-STRESS-CALCULATION-FOR-CURRENT-THICK" RULE

```
(DEFINE-RULE PERFORM-FREE-EDGE-STRESS-CALCULATION-FOR-CURRENT-THICK
   (:PRIORITY 50)
 (INSTANCE ?NEW-BOUND-LAYER IS NEW-BOUND-LAYER
        WITH ALTERNATIVE-FUNCTION INCREASE-AIRCRAFT-PAYLOAD
        WITH NEW-LAYER-THICKNESS ?JPCP-THICKNESS
        WITH AIRCRAFT-AND-ANNUAL-COVERAGES
        (?AIRCRAFT-MAIN-GEAR ?AIRCRAFT ?ANNUAL-COVERAGES
                             ?COVERAGE-RATIO ?HALF-GEAR-SPACING))
 (INSTANCE ?AIRCRAFT-MAIN-GEAR IS MAIN-GEAR
        WITH GEAR-LOAD ?GEAR-LOAD)
   THEN
 (INSTANCE SEILER-SINGLE-LAYER-STRESS-MODEL IS SINGLE-LAYER-STRESS-MODEL
        WITH ALTERNATIVE ?NEW-BOUND-LAYER
        WITH AIRCRAFT ?AIRCRAFT
        WITH GEAR-LOAD ?GEAR-LOAD
        WITH AIRCRAFT-MAIN-GEAR ?AIRCRAFT-MAIN-GEAR)
 (SEND-MSG 'SEILER-SINGLE-LAYER-STRESS-MODEL :FIND-FREE-EDGE-STRESS))
```

4.3.3.4 Forecaster And Economist

The Forecaster and Economist DPDM rule bases have not been implemented in AIRPACS at the present time because this research focused on the Planner and Designer DPDMs, who are the key participants in the rehabilitation design process. Since very little new knowledge will be represented in the Forecaster and Economist DPDMs, implementation was not critical to this research.

However, the method of implementation will follow the same logic that was used to represent the knowledge of the Planner, Constructor, Airfield Manager and Designer DPDMs. All surviving alternative instances will continue to maintain their identity and move to higher levels on the Blackboard. During this move, each object instance would continue to carry its own justification and design information. At the same time, additional information would be added to the existing information as has been previously described.

4.4 KBES USER INTERFACE

Figures 4-21 and 4-22 illustrate the graphical user interface environment that is currently built into AIRPACS. The user interface in AIRPACS allows users to create the airfield pavement system descriptions (APSD) for their airport, enter evaluation results for each JPCP section, enter design information for reconstruction and JPCP unbonded overlays, and control the level of rehabilitation design. The user interface was built using the Goldworks II graphics toolkit which operates on top of the Microsoft's Windows 2.11 environment.

FIGURE 4-21
GRAPHICAL USER INPUT SCREEN FOR ENTERING PCI DISTRESSES

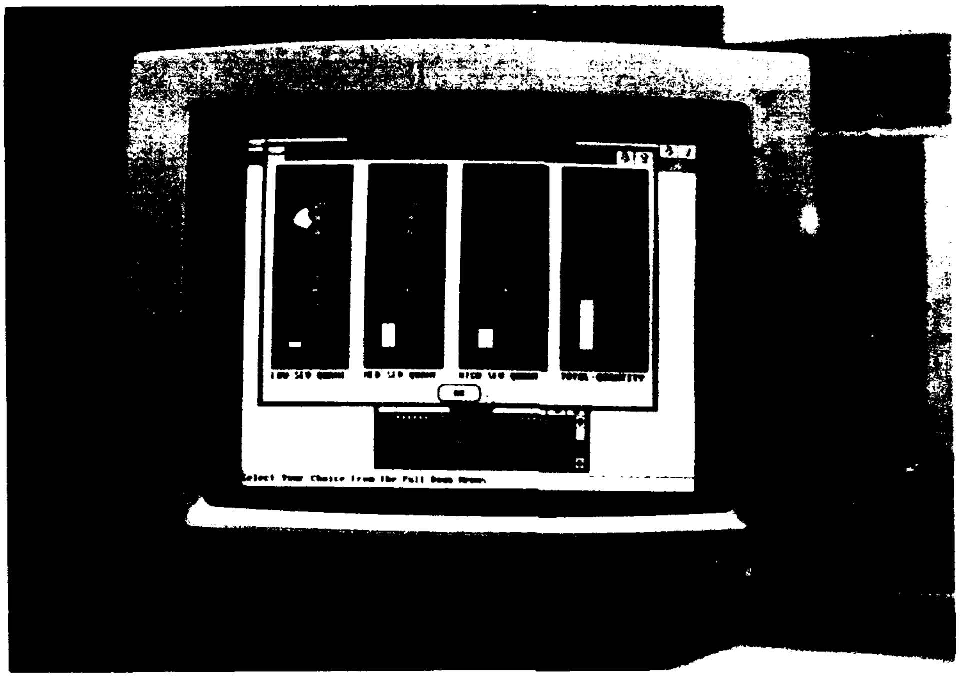
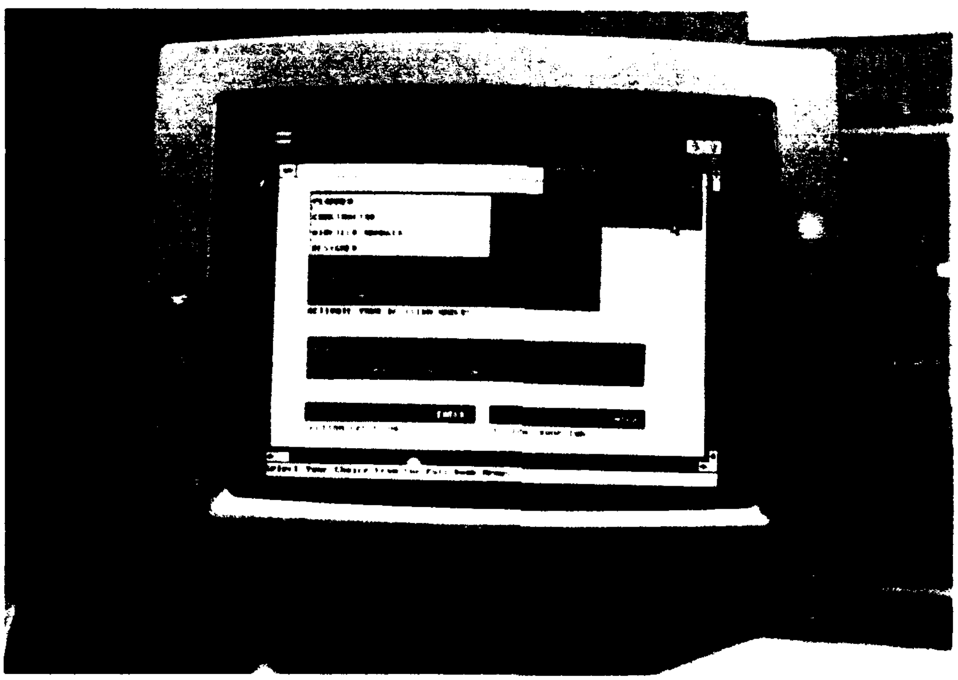


FIGURE 4-22
GRAPHICAL USER INPUT SCREEN FOR CONTROLLING REHABILITATION DESIGN



The graphics toolkit consists of an object-oriented environment with several predefined graphic images. Image classes consists of several types of popup menus, dials, gauges, xy-plots, text-images and fixed-menus. The user interface in AIRPACS uses this object-oriented environment and a forward-chaining inferencing strategy to help the user quickly enter information about the APSD and to review design output that is posted on the Blackboard.

Figure 4-21 shows how the PCI distress quantities can be quickly entered by using "gauge" objects and the "point and click" capabilities of a mouse. Figure 4-22 shows the design control panel that the user moves to after all APSD information has been entered. From this screen, the user can load all applicable design process decision makers (DPDMs), enter prerun input and control the level of JPCP rehabilitation design for an airport. A detailed illustration in Chapter 5 explains how APSD and prerun data is entered and how the user can review rehabilitation design output.

CHAPTER 5

AIRPACS VALIDATION TESTS

A knowledge-based expert system will not be used unless the system has been extensively tested under a variety of input conditions. AIRPACS was validated using several consultant reports [55, 72, 73, 74, 75] that were prepared by ERES Consultants, Inc. These reports were prepared for airports which are located in various climatic regions of the United States. In the section 5.2 of this chapter, AIRPACS recommendations for additional airports are summarized and compared to the consultant's recommendations. Finally, the results of a sensitivity analysis of the Designer design process decision maker (DPDM) in AIRPACS show how thicknesses change when key input values are changed in reconstruction and overlay structural designs.

5.1 DETAILED ILLUSTRATION OF AIRPACS

The consultant's report for Grand Forks AFB, North Dakota was used for a detailed illustration of the capabilities and limitations of AIRPACS. This section describes in detail an evaluation and design of Runway 37-17 at Grand Forks AFB, North Dakota. The runway was built in 1958 and has supported B-52 bomber aircraft for the past 42 years. However, the newer B-1 bomber will become the new mission aircraft in the near future. The consultant was asked to evaluate the existing condition of the runway and determine what actions are necessary to support the B-1 bomber for the next 20 years. The PCI of the 10 sections on the runway varied from 18 (very poor) to 57 (good). Thicknesses of the JPC layers in these sections ranged from 15 to 24 inches. Most sections showed load-, material-, and climate-related distresses.

5.1.1 AIRPACS Inputs

In the validation of AIRPACS, all user input values were the same as the values used by the consultant. The fact that another consultant may use different input values reiterates the requirement that an AIRPACS user must be a knowledgeable pavement engineer. Inputs for the detailed example are presented in the same order that data must be entered in AIRPACS when no existing airport data base file exists. Although Runway 37-17 consists of 10 pavement sections, JPCP section and evaluation inputs are shown for only section R4C.

5.1.1.1 <u>JPCP Section Inputs</u>

Section R4C is a keel section located in a "C" traffic area and has a PCI value of 38. The JPC layer is 19 inches thick and was constructed in 1958. This section is 3000 feet long and 200 feet wide and has joint spacings of 25 feet for both the longitudinal and transverse joints. Input data required by AIRPACS for this section are shown in Table 5-1. Of the 40 JPCP section input values, only 32 values have to be entered since the remaining values are default values provided by AIRPACS. The input data shown in Table 5-1 does not include evaluation results, which are required by all decision makers involved in the rehabilitation design process.

TABLE 5-1
JPCP SECTION DATA INPUT BY USER

R4C-SECTION-INPUT		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Part Of Facility	Runway-37-17	
Width (ft)	200	
Length (ft)	3000	
JPC Thickness (in)	19	
Surface Texture	Burlap	Grooved, Tined OR Burlap
Long Jt Spacing (ft)	25	
Trans Jt Spacing (ft)	25	
Long Contract Jt	Dummy-Groove-Doweled	Dummy-Groove Dummy-Groove-Doweled OR Dummy-Groove-Tie-Bar
Trans Contract Jt	Dummy-Groove-Doweled	
Long Construct Jt	Doweled	Doweled Keyed OR Keyed-Tie-Bar
Trans Construct Jt	Doweled	
Existing Base Layer?	Yes	Yes OR No
Base Texture	Gravel	Silt, Clay, Sand OR Gravel
Subgrade Texture	Clay	
Base Treatment	Untreated	Untreated Cement-Treated Lime-Treated OR Bituminous-Treated
Subgrade Treatment	Untreated	
Traffic Area	C	A, B, C OR D
Section Location	Keel	Keel, Facility-Edge OR Full-Facility-Width
Shoulder	Asphalt Concrete	Asphalt Concrete OR Portland Cement Concrete
Reactive Aggregate?	No	Yes OR No
Catch Basins?	No	Yes OR No

TABLE 5-1 (Cont)
JPCP SECTION DATA INPUT BY USER

R4C-SECTION-INPUT			
JPCP DISTRESSES	**PERCENT OF SLABS WITH DISTRESSES IN R4C**		
Corner Breaks	Low - 0.21		
Linear Cracking	Low - 15.73	Medium - 10.21	High - 1.77
"D" Cracking	Low - 23.65	Medium - 1.77	
Joint Seal Damage		Medium - 100	
Small Patch	Low - 41.35	Medium - 7.50	
Large Patch	Low - 28.65	Medium - 1.77	
Popouts	90.94		
Shattered Slabs		Medium - 0.42	
Shrinkage Cracking	2.50		
Joint Spalling	Low - 2.92	Medium - 0.21	
Corner Spalling	Low - 6.56	Medium - 5.00	High - 0.73

5.1.1.2 <u>JPCP Section Evaluation Inputs</u>

Since an evaluation knowledge-base does not exist in AIRPACS, the user must carefully select input values which will be used in the rehabilitation design process. When evaluation results are not available, an AIRPACS user who does not have extensive pavement experience should exercise caution when entering evaluation results. The evaluation results obtained by ERES Consultants, Inc. are presented in Table 5-2. When evaluation tests were not conducted for a specific area, it was assumed that there were no problems in that evaluation area. AIRPACS default values are used in these situations.

TABLE 5.2
EVALUATION RESULTS INPUT BY USER

R4C-FROST-EVALUATION		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Frost Protection	Unacceptable	Unacceptable OR Acceptable
Frost Heave	Systematic	None, Systematic OR Random

TABLE 5.2 (cont)
EVALUATION RESULTS INPUT BY USER

R4C-STRUCTURAL-EVALUATION		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Past Miner's Damage	0.40	Range 0.0 - 1.0
Design PCC Modulus Of Rupture (psi)	779	
Design PCC Modulus Of Elasticity (psi)	6600000	
Design "k" Value Beneath JPC Layer (psi/in)	210	

R4C-DRAINAGE-EVALUATION		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Base Drainage Time	Satisfactory	Unacceptable
Transverse Drainage Capacity	Satisfactory	
Longitudinal Drainage Capacity	Satisfactory	Marginal OR
Catch Basin Condition	Satisfactory	
Shoulder Condition	Satisfactory	Satisfactory

R4C-RATE-OF-DETERIORATION-EVALUATION		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Short Term Deterioration Rate	Normal	Low, Normal
Long Term Deterioration Rate	Normal	OR High

R4C-JOINT-EVALUATION		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Winter Trans LTE (%)	93	Range 0 - 100
Spring Trans LTE (%)	93	"
Summer Trans LTE (%)	93	"
Fall Trans LTE (%)	93	"
Joint Shape Factor	Satisfactory	Unacceptable, Marginal OR Satisfactory

TABLE 5.2 (Cont)
EVALUATION RESULTS INPUT BY USER

R4C-ROUGHNESS-EVALUATION		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Long Wavelength Roughness	Satisfactory	Unacceptable, Marginal
Short Wavelength Roughness	Satisfactory	OR Satisfactory

R4C-FRICTION-EVALUATION		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Expected Aircraft Braking Response	No-Hydroplaning-Problems-Expected	No-Hydroplaning-Problems-Expected Transitional-Hydroplaning-Problems Potential-For-Hydroplaning OR Very-High-Probability-Of-Hydroplaning

The drainage capacities shown in Table 5.2 refer to subsurface drainage pipe capacities. The base drainage time is considered satisfactory if the forces of gravity reduce the saturation level to 50 percent in 10 days [11]. In addition, the rates of deterioration refer to the structural rates of deterioration which are associated with PCI distresses that are load related. The joint shape factor refers to the shape factor of the joint sealant reservoir. Of the 21 evaluation input values, only 10 values have to be entered since the remaining values are default values provided by AIRPACS.

5.1.1.3 <u>Pavement Facility Inputs</u>

AIRPACS users can enter data for a pavement facility after the user creates the first JPCP section of a pavement facility. When the user is editing a section and then enters a name for the facility, such as "Runway-37-17" for the "Part Of Facility" data type in Table 5.1, a facility instance is created. This instance provides the framework for more information that describes the Grand Forks airfield. After the user enters values for section R4C, pavement facility data shown in Table 5.3 may be entered. For Runway 37-17, only 9 of the 20 input values have to be entered since the rest of the values are default values. Key data in this table are the type and characteristics of each aircraft that use this pavement facility.

TABLE 5-3
FACILITY DATA INPUT BY USER

GRAND-FORKS-RW-FACILITY-INPUT		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Airfield	Grand-Forks	
Facility Type	Runway	Apron, Taxiway OR Runway
Facility Use	Primary	Primary OR Secondary
Transverse Slope	Bi-Directional	Uni-Directional OR Bi-Directional
Percent Transverse Slope	0.75	
Operational Aircraft	C-141B, B-1 AND F-15E	
Aircraft Speed	Greater-Than-100-Knots	Less-Than-100-Knots OR Greater-Than-100 Knots
Formation Takeoffs?	No	Yes OR No
Are Aircraft Towed?	No	Yes OR No
Average Annual Departures	F-15E - 1250 C-141B - 2500 B-1 - 5000	
Gear Load	F-15E - 35.2 Kips C-141B - 152.5 Kips B-1 - 225.4 Kips	
Runway P/C Ratio	F-15E - 17.55 C-141B - 3.61 B-1 - 3.71	

After the user selects all aircraft that operate on Runway 37-17, AIRPACS automatically presents input screens that allow the user to change a limited number of aircraft characteristics. The user is allowed to select operational aircraft from a list of 65 aircraft used by the U.S. Air Force and commercial airlines. When an aircraft is selected, the user is allowed to input the average annual departures for that aircraft and change either the aircraft main gear load or the pass-to-coverage ratio. The full operational weight of each aircraft was selected for section R4C. Once all aircraft characteristics have been selected and all remaining facility information entered, the user again has the option of entering data for the remaining sections of Runway 37-17, or entering general airfield information about Grand Forks AFB. Since only one pavement facility (i.e. Runway 37-17) exists in the airfield database at this time, the user must enter additional JPCP section data or general airfield data.

5.1.1.4 General Airfield Inputs

AIRPACS users can enter general airfield data after the user creates the first pavement facility of that airport. When the user is editing a pavement facility and then enters a name for the airfield, such as "Grand-Forks" for the "Airfield" data type in Table 5.3, an airfield instance is created. This instance provides the framework for general information about the Grand Forks airfield (Table 5-4). Since AIRPACS can design rehabilitation options for only one airfield at a time, only one airfield instance can be created for this database. For the Grand Forks airfield, only 2 of the 8 input values have to be entered since the rest of the values are default values.

After data have been entered for at least one JPCP section, one pavement facility and the airfield, the user can proceed to the "Design Control Panel" screen of the built-in user interface and perform "prerun" actions. At this point, users must select the JPCP sections that they want to study. Once these sections are selected, AIRPACS needs additional prerun information about the selected sections before the rehabilitation study can begin.

TABLE 5-4
AIRFIELD DATA INPUT BY USER

GRAND-FORKS-DATA		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Climate Region	Intermediate-Freeze-Region	Wet-Freeze-Region Wet-Freeze-Thaw-Region Wet-No-Freeze-Region Intermediate-Freeze-Region Intermediate-Freeze-Thaw-Region Intermediate-No-Freeze-Region Dry-Freeze-Region Dry-Freeze-Thaw-Region OR Dry-No-Freeze-Region
Natural Drainage Index	Imperfectly-Drained	Very-Poorly-Drained Poorly-Drained Imperfectly-Drained Moderately-Well-Drained Well-Drained Somewhat-Excessively-Drained OR Excessively-Drained
Water Table Depth	25 ft	
High Ground Seepage?	No	Yes OR No
Mean Winter Temperature (F)	19	Number
Mean Spring Temperature (F)	49	"
Mean Summer Temperature (F)	72	"
Mean Fall Temperature (F)	49	"

5.1.1.5 <u>Prerun Inputs</u>

Prerun input includes construction information, JPCP reconstruction and unbonded overlay design information and additional data about the user-selected sections. Construction information that must be entered before the rehabilitation study begins is shown in Table 5-5. For the Grand Forks runway project, it was assumed that all contractors in the area are experienced with all types of pavement rehabilitation work for an airfield.

The final prerun information that must be input by the user is design information that AIRPACS needs if reconstruction or an unbonded JPCP overlay is feasible. Design information that was input for the rehabilitation design of section R4C is shown in Table 5-6. It should be noted that although keyed joints are offered as a choice for AIRPACS users, this type of joint should not be used when heavy aircraft, such as the B-1, use the pavement facility.

Table 5-7 shows additional section information that will affect the rehabilitation design for section R4C. Since the entire facility can be overlaid, the Planner DPDM assumes that there are no geometric grade transitions between R4C and other sections on Runway 37-17. In addition, the Planner assumes that there are no significant grade transition problems between the runway and intersecting taxiways. Although the user must enter general section information for each selected section, this data can be input very quickly since many of the default values apply for new designs.

For general R4C section prerun input, only 1 of the 6 values shown in Table 5-6 have to be entered since the rest of the default values are correct for this design scenario. For all prerun inputs, only 5 of 17 values have to be entered since the rest of the default values are correct. After all prerun input is entered, AIRPACS has sufficient information in the object-oriented data structure to conduct a rehabilitation design.

5.1.2 AIRPACS Outputs

Before the rehabilitation design can begin, the user must individually activate the Planner, Constructor, Airfield Manager and Designer knowledge-bases. Once these design process decision makers (DPDMs) are activated, the user initiates the forward-chaining inference strategy in AIRPACS. For the current prototype system, the rules will stop firing when the Designer DPDM has completed its work. The following sections present the output from each of these knowledge-bases as well as the justification statements that support their work.

TABLE 5-5
PRERUN CONSTRUCTION INPUT BY USER

CONSTRUCTION-INPUT		
DATA TYPE	**VALUE**	**CONSTRAINTS**
JPCP Rehabilitation Work Local Contractors Have No Experience With	None	
Allowable Facility Closure Period	More-Than-10-Days	Overnight 1-To-10-Days OR More-Than-10-Days
Construction Speed	Normal	Fast Track OR Normal
Project Scope Of Work	Large	Large OR Small
Aircraft Safety Clearance (ft)	200	

TABLE 5-6
PRERUN DESIGN INPUT BY USER

USER-DESIGN-INPUT		
DATA TYPE	**VALUE**	**CONSTRAINTS**
Long Construction Joint	Doweled	Doweled Keyed OR Keyed-Tie-Bar
Trans Contraction Joint	Doweled	
Long Contraction Joint	Dummy-Groove-Doweled	Dummy-Groove Dummy-Groove-Doweled OR Dummy-Groove-Tie-Bar
Trans Contraction Joint	Dummy-Groove-Doweled	
Design Concrete Modulus Of Elasticity (psi)	4000000	
Design Concrete Modulus Of Rupture (psi)	720	

TABLE 5-7
PRERUN GENERAL SECTION INPUT BY USER

R4C-GENERAL-SECTION-INPUT		
DATA TYPE	**VALUE**	**CONSTRAINTS**
New Mission?	Yes	Yes OR No
Design Life	20 years	
Overlay Entire Facility?	Yes	Yes OR No
Within 1000 Feet Of Runway End?	No	Yes OR No
Do Shops Control FOD?	Yes	Yes OR No
Slab Cracking Variation	Systematic	Systematic OR Localized

In addition, the work that the Forecaster and Economist knowledge-bases will perform when AIRPACS is enhanced is demonstrated using a Lotus 1-2-3 spreadsheet. The output from each of the DPDMs is presented in the order in which DPDMs work and place output on the Blackboard. The first DPDM that is allowed to work in the JPCP rehabilitation design process is the Planner. This DPDM will identify feasible structural improvements, drainage improvements, safety enhancements and maintenance repairs.

5.1.2.1 Section R4C Structural Improvements

The first area of study for the Planner is structural improvement. In AIRPACS, some type of structural improvement is always feasible when a new mission aircraft is being considered. If no pre-overlay repair is performed for section R4C, the only feasible structural improvement alternative is reconstruction. Normally, an unbonded JPCP overlay is feasible despite the PCI or surface condition, provided the overlay geometry is acceptable. However, in the case of section R4C, the Planner did not approve an unbonded JPCP overlay because the PCI is below 55 and damage from differential frost heave exists. The justifications that AIRPACS provides for the Planner's actions are shown in Table 5-8.

TABLE 5-8
PLANNER JUSTIFICATION STATEMENTS FOR STRUCTURAL IMPROVEMENTS

STATEMENT CATEGORY	JUSTIFICATION STATEMENTS
PLANNER-MISSION-STATEMENT	(TRAFFIC MAY OVERLOAD PAVEMENT) (CURRENT MISSION-TRAFFIC ACCEPTABLE) (19 INCH-PAVEMENT-FOR B-1 MAY-BE-ADEQUATE) (19 INCH-PAVEMENT-FOR C-141B MAY-BE-ADEQUATE) (19 INCH-PAVEMENT-FOR F-15E MAY-BE-ADEQUATE)
PLANNER-VISUAL-OBSERVATION	(PAVEMENT HAS NO SEVERE DURABILITY PROBLEMS) (PRIMARY RUNWAY STRUCTURAL-DISTRESSES TOLERABLE) (REACTIVE-AGGREGATE-DISTRESSES TOLERABLE) (CLIMATE-AND-MATERIAL-DISTRESSES TOLERABLE)
PLANNER-FATIGUE-STATEMENT	(FATIGUE DAMAGE IS UNACCEPTABLE) (NUMEROUS VISUAL-CRACKS AGREES-WITH FATIGUE-ANALYSIS) (COMPARE SURFACE CRACKS WITH FATIGUE ANALYSIS)
PLANNER-SURFACE-STRUCTURAL-STATEMENT	(OVERLAY GEOMETRY ACCEPTABLE) (STUDY OVERLAY OPERATIONAL AND GEOMETRIC LIMITATIONS)
PLANNER-PAVEMENT-SYSTEM-STATEMENT	(OVERLAYS ARE INFEASIBLE) (RECONSTRUCTION IS FEASIBLE) (STRUCTURAL IMPROVEMENT NEEDED)

When the Planner states that the mission traffic may overload the pavement, it may be referring to current or future aircraft traffic. Since the Planner states that the current mission traffic is acceptable, the only possible explanation for this statement is it is uncertain about the future traffic. For section R4C, a new mission was identified in the prerun input. Since the Planner does not have the knowledge and tools to confidently assess the structural impact of the new mission aircraft, it assumes a structural improvement is needed and lets the Designer analyze the situation in more detail.

5.1.2.2 Section R4C Drainage Improvements

Drainage improvements that are feasible for section R4C include longitudinal and transverse drainage pipe installation. Since the existing base course drainage time is acceptable, these alternatives will help move excess moisture further away from the pavement structure. The Planner's justification for drainage improvement decisions is shown in Table 5-9.

TABLE 5-9
PLANNER JUSTIFICATION STATEMENTS FOR DRAINAGE IMPROVEMENTS

(TEMPERATURE-AND-MOISTURE DO SUPPORT FROST-HEAVE) (BASE AND/OR SUBGRADE DRAINAGE ACCEPTABLE) (GRAND-FORKS HAS POOR-NATURAL-DRAINAGE) (GRAND-FORKS HAS SIGNIFICANT MOISTURE-SOURCES)

5.1.2.3 Section R4C Safety Enhancements

The Planner DPDM did not identify any safety improvements that were required for section R4C. Planner justification statements in Table 5-10 show there are no safety problems; therefore, no safety enhancement actions are required. If safety problems had existed, a safety enhancing overlay or grooving may have been recommended if no structural improvement was required.

Since structural improvements are necessary for section R4C, as well as other sections on Runway 37-17, no safety enhancing overlay would have been recommended, even if roughness, FOD potential or friction resistance had been unacceptable. For this situation, AIRPACS would explain what safety problems exist so the user knows that these problems must be corrected with the placement of a structural overlay or reconstruction of the JPCP section.

TABLE 5-10
PLANNER JUSTIFICATION FOR SAFETY ENHANCEMENT DECISIONS

```
(FUNCTIONAL PERFORMANCE SATISFACTORY)
(SURFACE PROFILE ACCEPTABLE)
(PRIMARY RUNWAY FOD-LEVEL ACCEPTABLE)
(AT-ALL-SPEEDS BURLAP SURFACE SKID-RESISTANCE ACCEPTABLE)
(PAVEMENT SHORT-WAVELENGTH ROUGHNESS SATISFACTORY)
(RUNWAY LONG-WAVELENGTH ROUGHNESS SATISFACTORY)
```

5.1.2.4 Section R4C Maintenance And Repair (M&R)

The Planner DPDM reviews the JPCP distresses that are present in this section and then selects various types of restoration and maintenance work. If the user wants to significantly improve the condition of the JPCP and has sufficient funds, then complete restoration work is a feasible option. Maintenance work is separated into three categories which will help the user prioritize work requirements for the maintenance crew. When facility closure time is limited or airport maintenance crews have a difficult time keeping up with repair requirements, more expedient repairs can be made to section R4C. Table 5-11 shows the types of repairs that AIRPACS recommends for R4C to improve the condition of this pavement section.

TABLE 5-11
REPAIR WORK RECOMMENDED BY THE PLANNER DPDM

AIRPACS REPAIR RECOMMENDATIONS	
REPAIR CATEGORY	**TYPE OF REPAIR**
R4C-Complete-Restoration (Repairs all JPCP distresses)	Slab Replacement (1) Partial-Depth-Patch (2) Joint-Reseal (3) Crack-Seal (4)
R4C-Complete-Maintenance (Repairs all JPCP distresses)	Partial-Depth-Patch (3) Joint-Reseal (2) Crack-Seal (1)
R4C-Critical-Repair (Repairs all JPCP distresses with medium- and high-severity levels)	Partial-Depth-Patch (3) Joint-Reseal (2) Crack-Seal (1)
R4C-Emergency-Repair (Repairs all JPCP distress with high-severity levels)	Partial-Depth-Patch (2) Crack-Seal (1)

NOTES
(1) - The numbers in parenthesis indicate the order in which the repairs were selected.
(2) - Although not required for R4C, joint load transfer restoration and joint restoration would only be considered for restoration repairs.

The repairs selected for each repair category for section R4C are based on a prioritized list of repairs and the types of repairs that are feasible for each distress type and severity. The types of repairs that can be made for the existing distresses in section R4C are shown in Table 5-12. These statements justify the types of repairs that the Planner selected in Table 5-11. AIRPACS lists the distresses shown in Table 5-12 from highest to lowest severity so the user can easily see which distresses will be repaired for each maintenance category.

TABLE 5-12
PLANNER JUSTIFICATION STATEMENTS FOR REPAIRS

FEASIBLE REPAIRS FOR R4C
(PARTIAL-DEPTH-PATCH FOR HIGH-SEVERITY CORNER-SPALLING)
(SLAB-REPLACEMENT FOR HIGH-SEVERITY LONG-TRANS-DIAG-CRACKING)
(PARTIAL-DEPTH-PATCH FOR HIGH-SEVERITY LONG-TRANS-DIAG-CRACKING)
(FULL-DEPTH-PATCH FOR HIGH-SEVERITY LONG-TRANS-DIAG-CRACKING)
(CRACK-SEAL FOR HIGH-SEVERITY LONG-TRANS-DIAG-CRACKING)
(PARTIAL-DEPTH-PATCH FOR MEDIUM-SEVERITY CORNER-SPALLING)
(JOINT-RESEAL FOR MEDIUM-SEVERITY CORNER-SPALLING)
(SLAB-REPLACEMENT FOR MEDIUM-SEVERITY JOINT-SPALLING)
(PARTIAL-DEPTH-PATCH FOR MEDIUM-SEVERITY JOINT-SPALLING)
(JOINT-RESEAL FOR MEDIUM-SEVERITY JOINT-SPALLING)
(FULL-DEPTH-PATCH FOR MEDIUM-SEVERITY JOINT-SPALLING)
(SLAB-REPLACEMENT FOR MEDIUM-SEVERITY SHATTERED-SLAB)
(CRACK-SEAL FOR MEDIUM-SEVERITY SHATTERED-SLAB)
(PARTIAL-DEPTH-PATCH FOR MEDIUM-SEVERITY LARGE-PATCH)
(CRACK-SEAL FOR MEDIUM-SEVERITY LARGE-PATCH)
(PARTIAL-DEPTH-PATCH FOR MEDIUM-SEVERITY SMALL-PATCH)
(CRACK-SEAL FOR MEDIUM-SEVERITY SMALL-PATCH)
(JOINT-RESEAL FOR MEDIUM-SEVERITY JOINT-SEAL-DAMAGE)
(PARTIAL-DEPTH-PATCH FOR MEDIUM-SEVERITY DURABILITY-CRACKING)
(CRACK-SEAL FOR MEDIUM-SEVERITY LONG-TRANS-DIAG-CRACKING)
(JOINT-RESEAL FOR LOW-SEVERITY CORNER-SPALLING)
(DO-NOTHING FOR LOW-SEVERITY CORNER-SPALLING)
(PARTIAL-DEPTH-PATCH FOR LOW-SEVERITY JOINT-SPALLING)
(JOINT-RESEAL FOR LOW-SEVERITY JOINT-SPALLING)
(DO-NOTHING FOR LOW-SEVERITY JOINT-SPALLING)
(DO-NOTHING FOR LOW-SEVERITY LARGE-PATCH)
(DO-NOTHING FOR LOW-SEVERITY SMALL-PATCH)
(JOINT-RESEAL FOR LOW-SEVERITY DURABILITY-CRACKING)
(DO-NOTHING FOR LOW-SEVERITY DURABILITY-CRACKING)
(CRACK-SEAL FOR LOW-SEVERITY DURABILITY-CRACKING)
(DO-NOTHING FOR LOW-SEVERITY LONG-TRANS-DIAG-CRACKING)
(CRACK-SEAL FOR LOW-SEVERITY LONG-TRANS-DIAG-CRACKING)
(DO-NOTHING FOR LOW-SEVERITY CORNER-BREAK)
(CRACK-SEAL FOR LOW-SEVERITY CORNER-BREAK)

After reviewing Tables 5-11 and 5-12, an AIRPACS user may want to know why full-depth patching was not listed as a M&R method and why slab replacement was only listed for restoration work. Full-depth patching is not listed as a restoration repair because slab replacement has a higher priority than full-depth patching in restoration. When AIRPACS selects slab replacement for restoration, this repair corrects all distresses that can also be corrected by full-depth patching in section R4C. Selection of the "slab replacement" repair also contributes more to PCI improvement than full-depth patching which is an AIRPACS restoration goal. Full-depth patching and slab replacement are not identified for any maintenance category because crack sealing and joint resealing are more expedient methods of repair. These maintenance repairs provide interim repairs for the PCI distresses in R4C until more time is available to make full-depth patching and slab replacement repairs.

5.1.2.5 Section R4C New Bound Layer

A new bound layer in AIRPACS refers to an overlay or a reconstructed JPCP pavement. The Planner DPDM identified reconstruction as the only feasible structural improvement alternative for section R4C. This alternative was designed as a new bound layer because it also survived critical reviews by the Constructor and Airfield Manager. As a result, the Designer placed the output shown in Table 5-13 on the Blackboard.

As expected, the B-1 is the aircraft that will cause the most damage in the future. Section R4C was designed for 5000 average annual departures of the B-1 using an unchannelized pass-to-coverage ratio of 3.71. Justification statements of the Constructor, Airfield Manager and Designer are shown in Table 5-14. Since the thickness of the new JPC layer is greater than the minimum allowable thickness of 5 inches, this alternative was approved by the Designer.

5.1.2.6 Section R4C New Bound Layer Performance

The Designer based the reconstruction thickness on the anticipated future traffic loads on section R4C, but the performance of this pavement will also depend on the climate. To demonstrate the capabilities of the Forecaster DPDM, a Lotus 1-2-3 spreadsheet was used to represent Equation 3.12 and estimate the PCI of section R4C if it is reconstructed. Figure 5.1 shows the expected performance of section R4C as a new JPCP for the next 20 years. This figure shows that if no repairs are made during this period, the PCI will be approximately 76 (very good) at the end of the design life specified in the prerun input. Normally, a PCI above 70 is acceptable for aircraft operations on a runway. Therefore, the Forecaster DPDM predicts that a reconstruction thickness of 20 inches will perform satisfactorily for the estimated future traffic loads and climatic conditions at Grand Forks AFB, North Dakota.

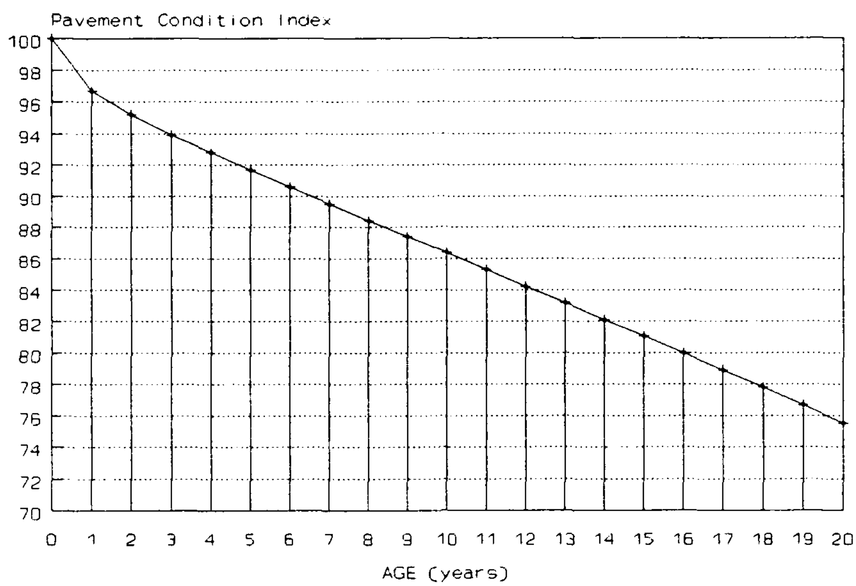
TABLE 5-13
DESIGNER OUTPUT FOR RECONSTRUCTION OF SECTION R4C

DATA TYPE	VALUE
Existing JPC Layer Thickness (in)	19.0
New JPC Layer Thickness (in)	20.0
Design Mr (psi)	720
Design Eo (psi)	4000000
Design "k" (psi/in)	210
Long Joint Spacing (ft)	25
Trans Joint Spacing (ft)	25
New Layer Long Construct Joint	Doweled
New Layer Long Contract Joint	None
New Layer Trans Construct Joint	Doweled
New Layer Trans Contract Joint	Dummy-Groove-Doweled
Critical Design Aircraft	B-1
Critical Edge Stress (psi)	388
Dowel Diameter (in)	1.5
Dowel Spacing (in)	18
Dowel Length (in)	20

TABLE 5-14
JUSTIFICATION STATEMENTS FOR RECONSTRUCTION DESIGN OF R4C

DECISION MAKER	JUSTIFICATION STATEMENTS
Constructor	(LOCAL-CONTRACTOR HAS AIRFIELD-RECONSTRUCTION-EXPERIENCE WITH SECTION-KEEL-REPLACEMENT) (LOCAL-CONTRACTOR HAS AIRFIELD-RECONSTRUCTION-EXPERIENCE WITH RECYCLE-RECONSTRUCTION) (LOCAL-CONTRACTOR HAS AIRFIELD-RECONSTRUCTION-EXPERIENCE WITH STANDARD-RECONSTRUCTION) (LOCAL-CONTRACTOR HAS AIRFIELD-RECONSTRUCTION-EXPERIENCE WITH DRAINAGE-WORK)
Airfield Manager	(AIRCRAFT OPERATIONS PERMIT ALTERNATIVE SECTION-KEEL-REPLACEMENT) (AIRCRAFT OPERATIONS PERMIT ALTERNATIVE RECYCLE-RECONSTRUCTION) (AIRCRAFT OPERATIONS PERMIT ALTERNATIVE STANDARD-RECONSTRUCTION)
Designer	(DO NOT USE LONGITUDINAL CONTRACTION JOINTS) (JOINT SPACING BASED ON STIFFNESS IS 25.0148 FEET) (EXISTING TRANSVERSE JOINT SPACING IS 25 FEET) (ALL USER SPECIFIED TRANSVERSE JOINTS ARE DOWELED SO GOOD LOAD TRANSFER WILL EXIST) (EXISTING LONGITUDINAL JOINT SPACING IS 25 FEET)

FIGURE 5-1
SECTION R4C PCI vs TIME CURVE



5.1.2.7 <u>Section R4C New Bound Layer Performance Costs</u>

Although a reconstructed section will perform very well over the next 20 years, the user may want to know the cost of this "good performance." This work is the responsibility of the Economist DPDM in AIRPACS. Once again, a Lotus 1-2-3 spreadsheet was used to perform the work of the Economist for the detailed example. The value of reconstruction is estimated by dividing the present worth of reconstruction by the area under the PCI vs. time curve, and by computing the Equivalent Uniform Annual Cost (EUAC). This cost analysis information helps users make more informed decisions when they select a rehabilitation alternative.

When the value of reconstruction is determined by using the present worth of this alternative and the PCI vs. time curve, the area underneath the curve (performance) shown in Figure 5-1 must be determined. For this example, the area is approximately 1730 PCI-point-years. Next, the present worth of the reconstruction alternative is computing using Equation 3.15. Initial construction costs and future maintenance work such as patching, slab replacement and joint resealing are included in the present worth calculations. If the total present worth of $6,105,000 is divided by the area (performance), the performance cost or value of reconstruction is $3,530 per PCI-point-year.

If the user is more comfortable with the traditional EUAC economic analysis, the total present worth can be used to determine the EUAC per square yard. If equation 3.16 and a discount rate of 4 percent are used for the 20-year analysis period, the EUAC will be $6.74 per square yard. The performance costs and the EUAC should help the user decide if reconstruction of section R4C is within the budget. Up to this point, AIRPACS actions and recommendations have been made for section R4C in its current condition, but in reality a pavement engineer should consider the effect of preoverlay repair.

5.1.2.8 Preoverlay Repair

Preoverlay repair may improve the pavement condition to the point that an asphalt structural overlay is not desirable or the surface condition is acceptable for a bonded overlay. Restoration would have the additional effect of changing the required structural thicknesses if shattered or cracked slabs are replaced because AIRPACS uses this information to estimate past fatigue damage in certain scenarios. Since preoverlay repair can be a vital part of JPCP rehabilitation, its effect is considered for section R4C and the remaining sections on Runway 37-17.

Preoverlay repair in this example includes replacement of shattered slabs, resealing the existing joints, sealing the cracks in all medium- and high-severity cracked slabs, replacement of medium-severity small and large patches, patching medium-severity "D" cracks, patching medium-severity joint spalls, and patching medium- and high-severity corner spalls. This repair work leaves section R4C with the distresses shown in Table 5-15. Since the PCI is much higher after preoverlay repair, the Planner DPDM eliminates reconstruction as a feasible alternative for some sections and identifies an unbonded JPCP overlay as the preferred alternative.

5.1.2.9 Rehabilitation Cost Summary For All Runway Sections

Figures 5-2 and 5-3 show the alternatives that AIRPACS recommends and the high cost of reconstruction. Whenever reconstruction and an unbonded JPCP overlay are feasible for a section of Runway 37-17, AIRPACS shows that reconstruction is much more expensive. The consultant did not investigate reconstruction in great detail because this option is very expensive and it would

TABLE 5-15
DISTRESSES AFTER PREOVERLAY REPAIR

R4C-SECTION-DISTRESSES	
JPCP DISTRESSES	**QUANTITY (%)**
Corner Breaks	Low - 0.21
Linear Cracking	Low - 27.71
"D" Cracking	Low - 23.65
Small Patch	Low - 56.6
Large Patch	Low - 30.42
Popouts	No Severity - 90.94
Shrinkage Cracking	No Severity - 2.50
Joint Spalling	Low - 2.92
Corner Spalling	Low - 6.56

require a long-term closure of the runway. With the exception of section 6A, the consultant recommended a JPCP unbonded overlay for all sections shown Figures 5-2 and 5-3.

Without preoverlay repair, AIRPACS does not consider an unbonded overlay for sections 4C and 9C since the PCI is below 40 and frost protection is inadequate. For these sections, the consultant recommends reinforcing the unbonded overlay to minimize the damage that may occur from future frost heave and settlement. AIRPACS did not make this recommendation since the prototype considers only JPCP overlays.

The consultant's analysis showed that the load-carrying capacity of section 6A is adequate for the new B-1 mission aircraft. However, AIRPACS designed a new reconstruction thickness because the PCI is below 40 and a new mission aircraft will be deployed to Grand Forks AFB. The Planner DPDM identified reconstruction and an unbonded JPCP overlay as being feasible, but the Designer DPDM found that there was no requirement for a structural overlay. Thus, AIRPACS disapproved the JPCP unbonded overlay alternative and only reconstruction of section 6A was considered by the Forecaster and Economist DPDMs. Since it is unlikely that an expert would recommend a structural improvement without any preoverlay repair, several more validation runs were made which show the benefit of preoverlay repair.

FIGURE 5-2
PERFORMANCE COSTS FOR REHABILITATION WITH NO PREOVERLAY REPAIR

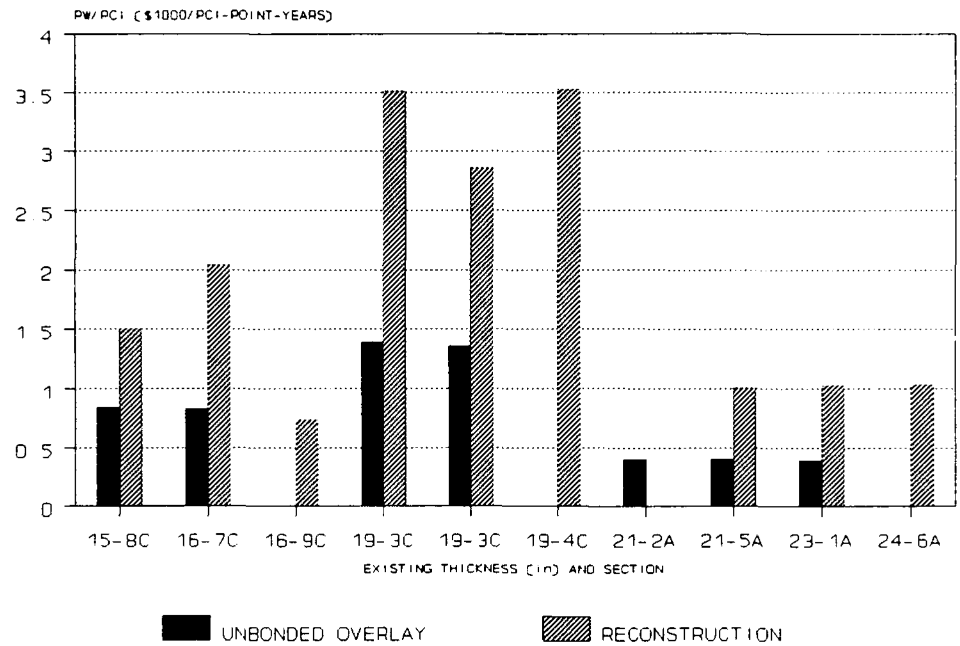
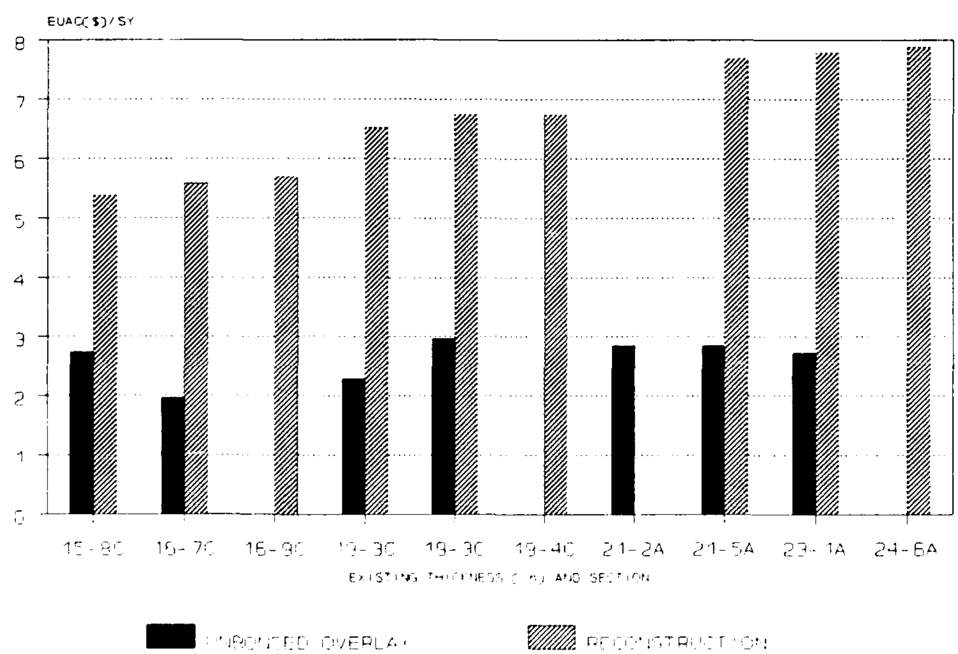


FIGURE 5-3
EUAC FOR REHABILITATION WITH NO PREOVERLAY REPAIR



When preoverlay repairs are made, Figures 5-4 and 5-5 show that AIRPACS frequently recommends an unbonded JPCP overlay which is the preferred alternative of the consultant. However, an unbonded overlay remains infeasible for section 9C since the PCI is still very low, despite the preoverlay repairs, and because this alternative would not significantly improve frost protection. Another effect of preoverlay repair is that the Planner DPDM no longer identifies reconstruction as feasible for section 6A. An unbonded overlay is feasible for this section, but the Designer once again disapproves this alternative since section 6A can structurally support the future 20-year traffic of the B-1 bomber.

Figures 5-4 and 5-5 both demonstrate the high cost of reconstruction relative to the unbonded overlay, but Figure 5-4 also provides additional information on the relative cost of rehabilitation for each section. The PCI performance cost for a section may be higher than another section for two reasons. The performance (area underneath the PCI vs time curve) of a rehabilitation option may be poorer, or the present worth of a rehabilitation option may be much higher than another section.

Figure 5-4 shows that the performance costs associated with reconstruction are much higher than the performance costs associated with an unbonded overlay for each section on the Runway 37-17. Since Figure 5-5 shows that there is little difference in cost for a rehabilitation alternative among all the JPCP sections, the only cause for a difference in performance costs for that same alternative is project scope. Therefore, the user could review Figures 5-4 and 5-5 and realize that AIRPACS recommends the more expensive reconstruction option for section 9C, but this section is a small part of the total scope of work required to structurally improve Runway 37-17.

5.1.2.10 <u>Design Thicknesses and Joints</u>

Besides the feasibility and costs of various rehabilitation alternatives, another area of high interest for many pavement engineers is how well does the Designer DPDM perform. The preceding discussion demonstrated that in general, both AIRPACS and the consultant agree that a JPCP unbonded overlay is the preferred rehabilitation alternative. But how do their joint spacings, joint types and thickness recommendations compare?

FIGURE 5-4
PERFORMANCE COSTS FOR REHABILITATION WITH PREOVERLAY REPAIR

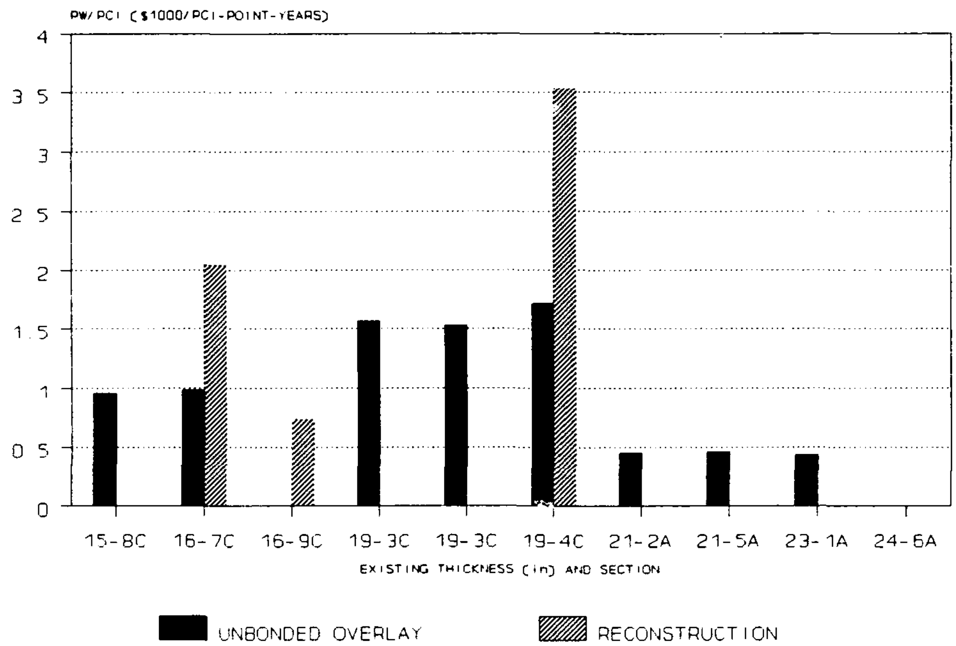


FIGURE 5-5
EUAC FOR REHABILITATION WITH PREOVERLAY REPAIR

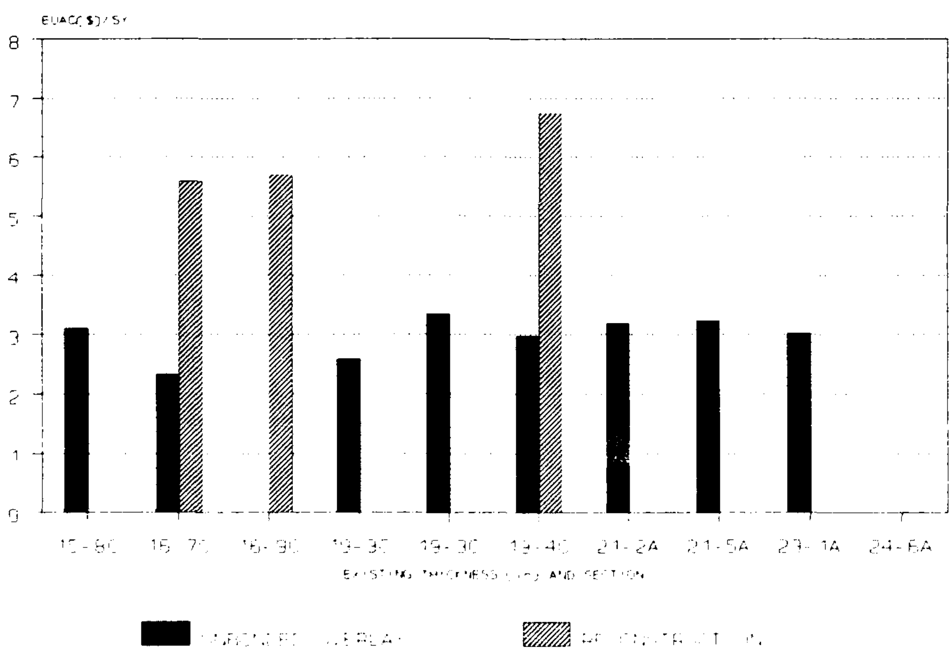
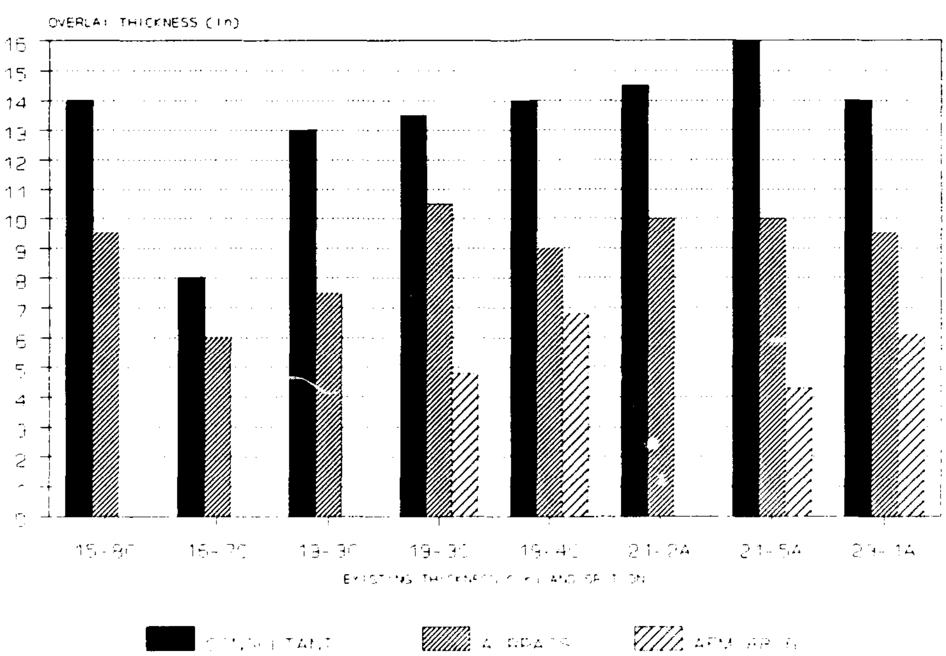


Figure 5-6 compares the JPCP unbonded thickness recommendations of AIRPACS, the consultant, and those obtained using Air Force Manual (AFM) 88-6. This figure shows that 50 percent of the time AFM 88-6 did not recognize the need for a structural improvement. In addition, the JPCP unbonded overlay thicknesses recommended by AIRPACS are significantly less than the consultant's recommendation, which does not include a safety factor. AIRPACS computes these unbonded overlay thicknesses using mechanistic, heuristic and empirical methods.

After the validation tests were complete, the finite element program ILLI-SLAB was used to determine the stress ratio (σ/Mr) in the existing JPC layer when each section in Figure 5-6 is overlaid with an unbonded JPCP. The stress ratios vary from 0.48 to 0.72 for the thicknesses recommended by the consultant and they vary from 0.52 to 0.75 for the thicknesses recommended by AIRPACS. Thus, the validation tests show that the JPCP unbonded overlay design procedure in AIRPACS provides reasonable results although a higher amount of cracking may occur in the existing JPCP. Since the JPCP overlay does not receive any significant amount of fatigue damage for the thicknesses recommended by the consultant or AIRPACS, an unresolved question is how much cracking should be permitted in an existing JPCP that is overlaid with an unbonded JPCP?

FIGURE 5-6
COMPARISON OF JPCP UNBONDED OVERLAYS FOR THE GRAND FORKS RUNWAY



Joint spacing recommendations for an unbonded overlay must be carefully selected to insure that high curling and warping stresses will not lead to premature failure of the overlay. Table 5-16 shows joint spacing recommendations made by AIRPACS and the FAA for JPCP unbonded overlays, and for reconstruction of the sections on the runway. The thickest overlay AIRPACS recommends is 10.5 inches for section R3C-2. For this section, AIRPACS recommends joint spacings of 12.5 feet and 13.25 feet.

It is important to note that AIRPACS joint spacing recommendations depend not only on the radius of relative stiffness, ℓ, but also on the dimensions of the pavement section. Therefore, a section may have a shorter joint spacing than a section with a lower overlay ℓ because the section is narrower or shorter.

Since AIRPACS and the consultant disagreed on the unbonded overlay thicknesses for several sections, joint spacing recommendations will differ since thickness is one of the key factors used to select joint spacings. The consultant recommended overlay unbonded thicknesses that ranged from 12 to 14 inches and joint spacings of 15 feet for all JPCP unbonded overlays. The consultant's joint spacing recommendation of 15 feet is equal to 4.13 times the radius of relative stiffness, ℓ. The unbonded JPCP overlay joint spacings in AIRPACS are based on a stiffness of 4ℓ.

TABLE 5-16
JOINT SPACING RECOMMENDATIONS FOR THE GRAND FORKS RUNWAY

SECTION	JPCP UNBONDED OVERLAY				JPCP RECONSTRUCTION			
	LONG JOINT		TRANS JOINT		LONG JOINT		TRANS JOINT	
	AIRPACS	FAA	AIRPACS	FAA	AIRPACS	FAA	AIRPACS	FAA
R1A	12.50	20	12.25	20	30.00	25	31.25	25
R2A	13.75	20	13.25	20				
R3C-1	10.75	12.5	11.00	15	25.00	25	23.00	25
R3C-2	12.50	20	13.25	20	25.00	25	25.25	25
R4C	12.50	20	12.50	20	25.00	25	25.25	25
R5A	13.75	20	14.00	20	37.50	25	33.25	25
R6A					30.00	25	31.25	25
R7C	8.25	12.5	9.25	15	25.00	25	21.50	25
R8C	12.50	20	13.50	20	25.00	25	21.50	25
R9C					25.00	25	21.50	25

NOTE: All joint spacings in Table 5-16 are based on the thicknesses AIRPACS recommends.

Since the consultant did not investigate reconstruction in great detail, reconstruction thicknesses were not calculated using a mechanistic procedure. Therefore, AIRPACS thicknesses were compared to those thicknesses the consultant obtained using AFM 88-6. Figure 5-7 shows that in all cases, the thicknesses recommended by AIRPACS are higher than the thicknesses obtained using AFM 88-6. AIRPACS results shown in Figure 5-7 are based on a stress load transfer efficiency (SLTE) of 54 percent that is obtained using doweled transverse joints. The discrepancies appear to be greater for "C" traffic areas that have a low number of design passes for the B-1. One of the reasons for the difference in design thicknesses may be due to the sensitivity of fatigue damage prediction equations. When the number of design passes is very low, a small change in the pavement edge stress leads to a relatively large change in allowable coverages to concrete fatigue failure.

The Grand Forks AFB runway design showed what inputs are required to run AIRPACS and how the output from AIRPACS compares with the recommendations that were made by the consultant. A structural improvement is required if the Air Force wants to have the B-1 bomber operate on this runway for the next 20 years. For most of the sections, both AIRPACS and the consultant agree that an unbonded overlay is the preferred rehabilitation alternative. Despite the fact that AIRPACS recommends a JPCP unbonded overlay thickness that is less than the consultant's recommendation, the stress ratios in the existing JPCP are not significantly different.

The Grand Forks runway has JPCP sections that are thicker than most airport pavements. Since the consultant did not perform a mechanistic reconstruction design for any section on the runway and because the JPCP sections are very thick, further validation tests were conducted for airports with thinner pavements. Since the consultant performed reconstruction designs at many of these airports, it is possible to compare AIRPACS, consultant and AFM 88-6 design recommendations, as illustrated in the following sections.

FIGURE 5-7
COMPARISON OF RECONSTRUCTION THICKNESSES FOR THE GRAND FORKS RUNWAY

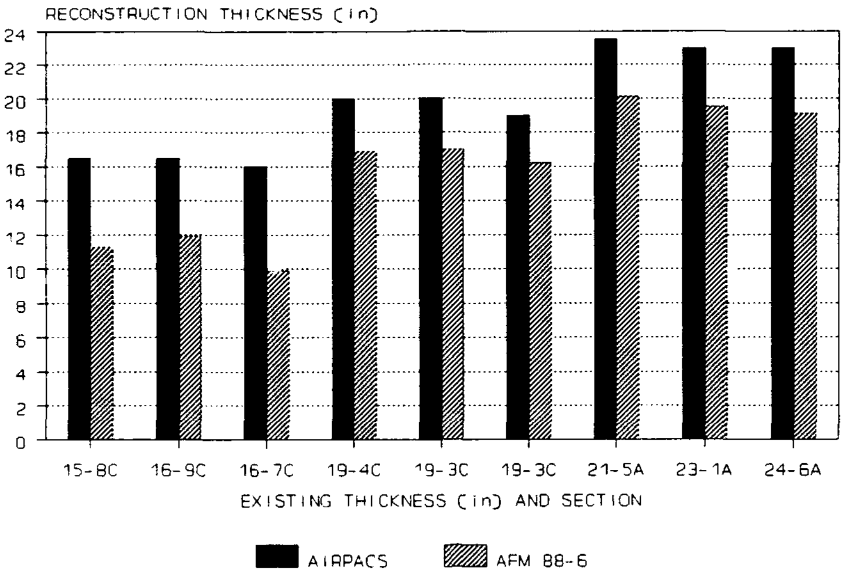
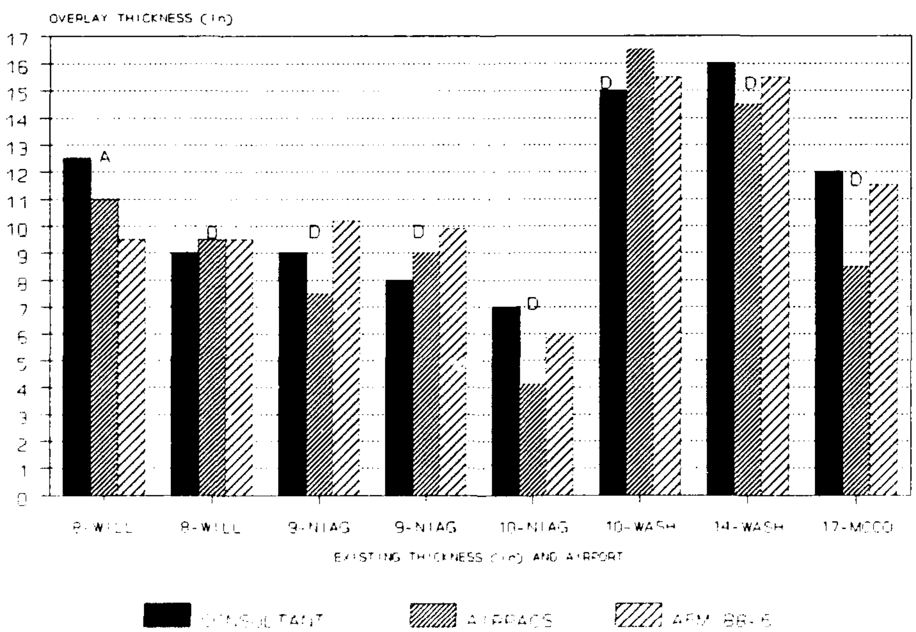


FIGURE 5-8
WILLARD-NIAGARA-WASHINGTON-McCONNELL JPCP UNBONDED OVERLAY THICKNESSES



D - DOWELED [illegible] A - AGGREGATE INTERLOCK

5.2 ADDITIONAL AIRPORT VALIDATION TESTS

Additional airports included in the validation tests are Willard Airport, Illinois; Niagara Falls Airport, New York; Washington National Airport, Virginia and McConnell AFB, Kansas. Whenever the consultant recognized a need for structural improvements at these airports, AIRPACS also identified feasible structural improvements. Therefore, this section focuses on the feasible structural improvements recommended by AIRPACS and the consultant.

5.2.1 JPCP Unbonded Overlays

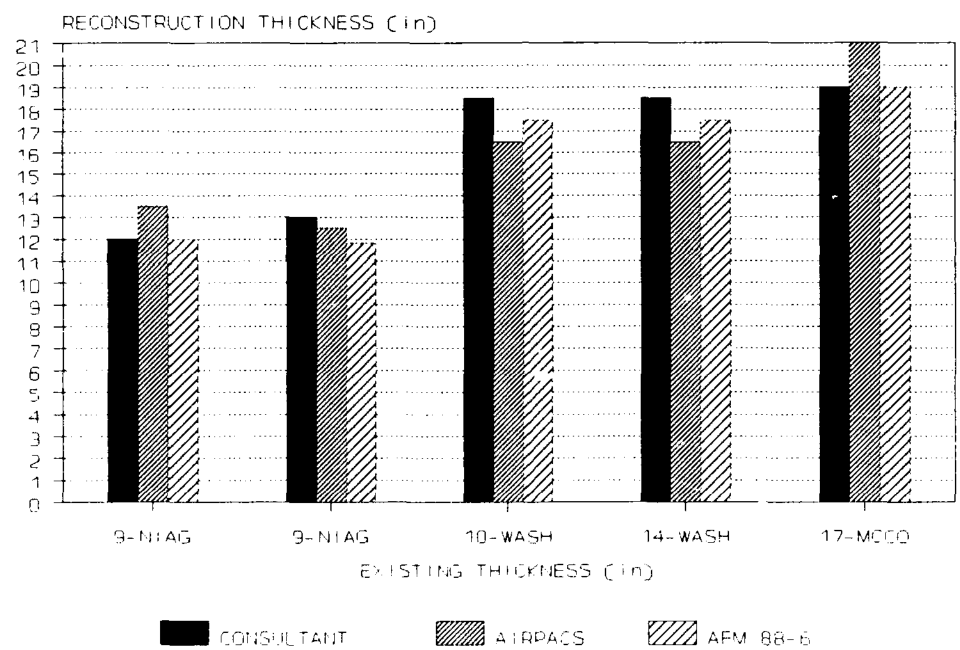
Figure 5-8 shows the unbonded overlay thicknesses that were recommended for each of these airports. Although the thicknesses AIRPACS recommends often agree with the consultant, AIRPACS underestimates the unbonded overlay thickness for the existing 10 inch apron at the Niagara Falls airport and the existing 17-inch apron at McConnell AFB. The critical aircraft for the apron at Niagara Falls is the F-15C/D while the critical aircraft at McConnell AFB is the B-1B bomber. One of the reasons for the difference in overlay thicknesses at McConnell AFB is that AIRPACS considers aircraft loadings at the transverse joint only. At McConnell AFB, the consultant analyzed loads at the longitudinal joint, which led to a higher slab edge stress.

Proponents of the elastic layer approach for JPCP pavements may argue that unbonded JPCP overlay thicknesses can be consistently estimated using an elastic layer program. However, the detailed illustration using Grand Forks AFB pointed out a major weakness of this approach, which is the inability to consider edge stress and load transfer across a joint. Figure 5-8 further emphasizes this weakness of the elastic layer design method. The two examples for Willard airport are designs for the same section under the same loading conditions. However, in one case dowels are used while in the next instance load transfer across the transverse joints depends entirely on aggregate interlock. For all other sections shown in Figure 5-8, the JPCP overlay is doweled. Overlay thicknesses recommended by the consultant and AIRPACS both recognize the benefit of improved load transfer through the use of dowels. Thus, AIRPACS displays one of its advantages over the AFM 88-6 design procedure, which is the ability to account for different load transfer efficiencies across the joints.

5.2.2 JPCP Reconstruction

Figure 5-9 shows that there are no large differences in reconstruction thicknesses that were determined by AIRPACS, the consultant or AFM 88-6. The two sections shown for Niagara Falls are two different apron sections and both use dowels for load transfer across the joints. The reconstruction thicknesses for Niagara Falls should be almost the same since the only variable that changes in the design is the "k" value beneath the new JPCP. For Washington National Airport there is no difference in the "k" value since a stabilized base is used. For this design, the consultant used a "k" value of 430 psi/in, but a "k" value of 200 psi/in was used as input to AIRPACS to consistently test the system. AIRPACS always uses a "k" value of 200 psi/in for a stabilized base or for an unbonded JPCP overlay when the new overlay is more than twice as stiff as the base JPC layer.

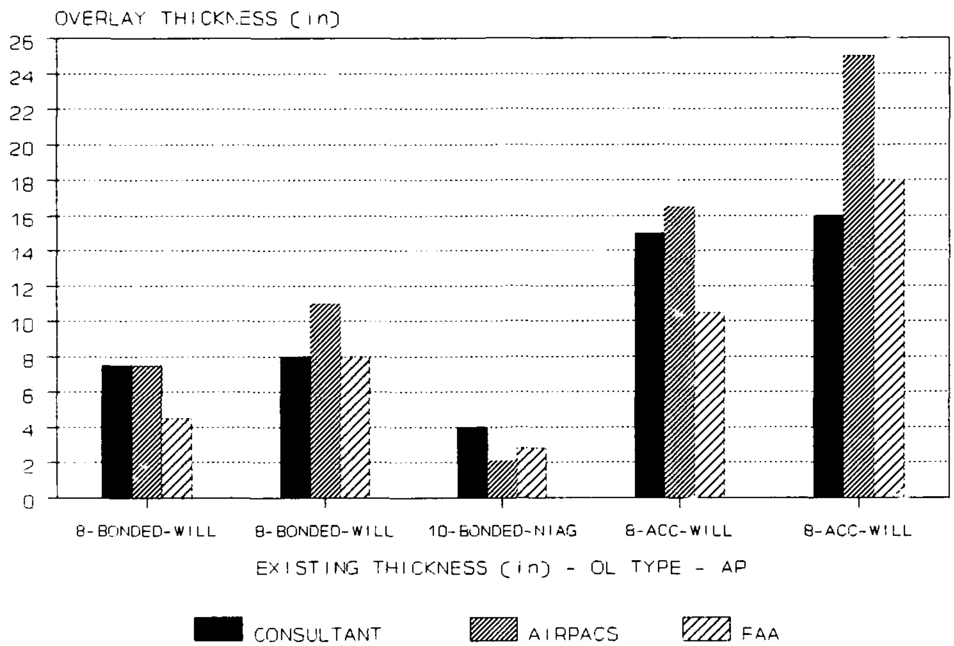
FIGURE 5-9
NIAGARA-WASHINGTON-McCONNELL JPCP RECONSTRUCTION THICKNESSES



5.2.3 JPCP Bonded And Asphalt Overlays

Figure 5-10 shows the validation results for bonded JPCP and AC overlays at Willard and Niagara Falls airports. Two thicknesses are shown for each type of overlay at Willard airport because two future traffic scenarios were considered in the validation study. In one case the future traffic consists of 2400 annual passes of a B-737 aircraft while the other scenario considers the impact of 1200 annual passes of a MD-80 aircraft. Figure 5-10 shows that with

FIGURE 5-10
WILLARD-NIAGARA JPCP BONDED AND AC OVERLAY THICKNESSES



the exception of one of the AC overlays, AIRPACS generally agrees with the results of the mechanistic analyses and the FAA design procedure.

The degree of agreement among the three design methods for both the AC and JPCP bonded overlays primarily depends on the existing load transfer efficiencies used in the analysis. The FAA method always assumes a stress load transfer efficiency of 25 percent. However, AIRPACS and other mechanistic methods use deflection load transfer efficiencies measured in the field which are used to compute the stress load transfer efficiencies.

Even in these cases, however, the results are heavily influenced by the relationship between deflection and stress load transfer efficiencies. For the consultant reports used in the validation tests, the consultant used one curve for the DLTE vs. SLTE relationship. The use of four DLTE vs. SLTE curves by AIRPACS is the primary reason that AIRPACS shows higher structural thicknesses for JPCP bonded and asphalt structural overlays than the consultant when the JPCP transverse joint is the critical loading location.

5.2.4 Validation Test Summary

Table 5-17 summarizes the feasibility comparisons between the Planner DPDM in AIRPACS and the consultant. It is important to note that a rehabilitation alternative may be feasible, but this does not imply that a structural improvement is necessary. For many of these sections, AIRPACS reviewed the feasibility of these structural alternatives because of a new mission aircraft. Likewise, the consultant reviewed all potential structural alternatives and screened out less desirable options. Since a mechanistic analysis requires a considerable work effort, this screening process allows the consultant to develop detailed designs for only those alternatives that the client is likely to select.

The validation tests show that AIRPACS generally agrees with the consultant's recommended JPCP rehabilitation alternative. The Designer DPDM provides reasonable structural designs for reconstruction, JPCP bonded and unbonded overlays and AC overlays.

5.3 SENSITIVITY ANALYSIS

Although the validation tests demonstrate many of the strengths and weaknesses of AIRPACS, these tests do not indicate how the Designer DPDM responds to changes in key variables in a structural design. Since there were design thickness discrepancies between AIRPACS and the consultant, a sensitivity analysis was conducted to investigate some of the discrepancies noted earlier.

Variables that were studied in the sensitivity analysis include the existing concrete modulus of rupture (Mr), existing concrete modulus of elasticity (Eo), annual aircraft departures, aircraft operational weights, past Miner's damage, and the structural condition index (SCI). These variables were analyzed because the consultant must select values for these variables that will be used in the structural design. The values that are selected for a structural design often vary among consultants and may lead to different structural thicknesses for a JPCP. For this reason, each variable is tested at three levels. The variables that were held constant in this analysis are shown in Table 5-18. Results of this study show how sensitive or insensitive the overlay or reconstruction thickness is to a change in one of the variables.

The results of the sensitivity study are presented by showing the effects of two variables at one time. Each figure shows the results for a JPCP bonded overlay, JPCP unbonded overlay, asphalt overlay and reconstruction.

TABLE 5-17
STRUCTURAL FEASIBILITY COMPARISONS

AIRPORT & SECTION	JPCP UNBONDED OVERLAY		JPCP BONDED OVERLAY		ASPHALT OVERLAY		RECONSTRUCTION	
	CONSULTANT	AIRPACS	CONSULTANT	AIRPACS	CONSULTANT	AIRPACS	CONSULTANT	AIRPACS
Grand Forks R1A	F	F	NF-1,4	NF-1,2 *FP	NF-6	NF-7	NF-5,6	F
Grand Forks R2A	F	F	NF-1,4	NF-1,2 *FP	NF-6	NF-7	NF-5,6	NF-2
Grand Forks R3C-1	F	F	NF-1,4	NF-1,2	NF-6	F	NF-5,6	F
Grand Forks R3C-2	F	F	NF-1,4	NF-1,2	NF-6	F	NF-5,6	F
Grand Forks R4C	F	NF-2,8 *FP	NF-1,4	NF-1,2,8	NF-6	NF-2,8	NF-5,6	F
Grand Forks R5A	F	F	NF-1,4	NF-1,2	NF-6	NF-7	NF-5,6	F
Grand Forks R6A	F	F	NF-1,4	NF-1,2	NF-6	NF-7	NF-5,6	F
Grand Forks R7C	F	F	NF-1,4	NF-1,2	NF-6	NF-2 *FP	NF-5,6	F
Grand Forks R8C	F	F	NF-1,4	NF-1,2	NF-6	F	NF-5,6	F
Grand Forks R9C	F	NF-2,8	NF-1,4	NF-2,8	NF-6	NF-2,8	NF-5,6	F
Grand Forks R10C	F	F	NF-1,4	NF-1,2	NF-6	F	NF-5,6	NF-2
McConnell Apron	F	F	NF-1,4	NF-1,2	NF-6,7	NF-7	NF-5,6	F
Wash National A1A	F	F	NF-4	F	NF-3,6	NF-7	F	F
Wash National A2A	F	F	NF-4	NF-2	NF-3,6	NF-7	F	F

REASONS FOR ALTERNATIVE INFEASIBILITY

(1) "D" cracking unacceptable
(2) PCI unacceptable (Too low or too high)
(3) Overlay geometry unacceptable
(4) Preoverlay repair is expensive
(5) Long-term closure period is unacceptable
(6) Rehabilitation option is very expensive
(7) Jet fuel spillage possible
(8) Unacceptable frost damage
(9) Unacceptable subsurface drainage

NOTES

(1) NF - Not feasible
(2) F - feasible
(3) FP - feasible with pre-overlay repair

TABLE 5-17 (cont)
STRUCTURAL FEASIBILITY COMPARISONS

AIRPORT & SECTION	JPCP UNBONDED OVERLAY		JPCP BONDED OVERLAY		ASPHALT OVERLAY		RECONSTRUCTION	
	CONSULTANT	AIRPACS	CONSULTANT	AIRPACS	CONSULTANT	AIRPACS	CONSULTANT	AIRPACS
Yeager Orig Apron	NF-3	F	F	F	NF-3	NF-7	F	F
Yeager Apron Ext	NF-3	F	F	F	NF-3	NF-7	F	F
Niagara A1A	NF-3	F	NF-1	NF-2	NF-7	NF-7	F	F
Niagara A2A	F	F	NF-1	NF-1,2	NF-7	NF-7	F	F
Niagara A3A	F	F	NF-1	NF-1,2	NF-7	NF-7	F	F
Niagara A4A	F	F	F	F	NF-7	NF-7	NF-2	NF-2
Niagara A5A	NF-3	F	NF-2	NF-2	NF-7	NF-7	F	F

REASONS FOR ALTERNATIVE INFEASIBILITY

(1) "D" cracking unacceptable
(2) PCI unacceptable (Too low or too high)
(3) Overlay geometry unacceptable
(4) Preoverlay repair is expensive
(5) Long-term closure period is unacceptable
(6) Rehabilitation option is very expensive
(7) Jet fuel spillage possible
(8) Unacceptable frost damage
(9) Unacceptable subsurface drainage

NOTES

(1) NF - Not feasible
(2) F - feasible
(3) FP - feasible with pre-overlay repair

TABLE 5-18
CONSTANTS IN THE SENSITIVITY ANALYSIS

VARIABLE	VALUE
Airport Location	Willard Airport, Savoy, IL
Design Aircraft	B-727
Maximum Operation Gear Weight	96,800 lbs
Design Period	20 years
Design Deflection Load Transfer Efficiencies For JPCP Bonded And Asphalt Overlays	Winter - 35% Spring - 35% Summer - 35% Fall - 35%
Design Deflection Load Transfer Efficiencies For JPCP Unbonded Overlays And Reconstruction (Doweled)	Winter - 85% Spring - 85% Summer - 85% Fall - 85%
New JPC Layer Ec	4,000,000 psi
New JPC Layer Mr	700 psi
"k" Beneath The 8 Inch JPC Layer	82 psi/in

In several instances, one or both variables have no effect on reconstruction. For example, past Miner's damage and the existing JPCP Eo and Mr values have no effect on reconstruction.

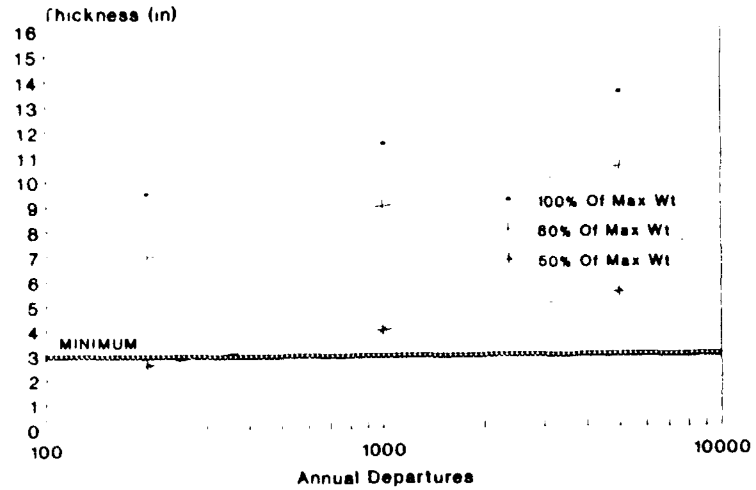
AIRPACS does not recommend a structural alternative if the thickness is below a minimum thickness that is acceptable for a specific alternative. The minimum thicknesses for each alternative type are noted in Figures 5-11 to 5-16. The Designer DPDM was modified slightly for the sensitivity analysis so it would not delete the alternative if the Designer calculated a thickness that was below the minimum. This allows the reader to appreciate the sensitivity of the Designer's work for extreme changes in all variables. However, during the validation tests, any alternative that had a thickness below the minimum was automatically deleted by the Designer DPDM. The first two variables presented in the sensitivity analysis, annual departures and operation weight, are the two variables that have the most significant effect on structural thicknesses.

5.3.1 Annual Departures vs. Aircraft Operational Weight

In Figure 5-11 the number of annual departures of a B-727 are plotted against thickness for three levels of aircraft weight. Gear loads of 48.4, 77.4 and 96.8 kips correspond to operational weights of 50 (empty), 80 and 100 percent of the maximum aircraft weight. Runs were made using departure levels of 200,

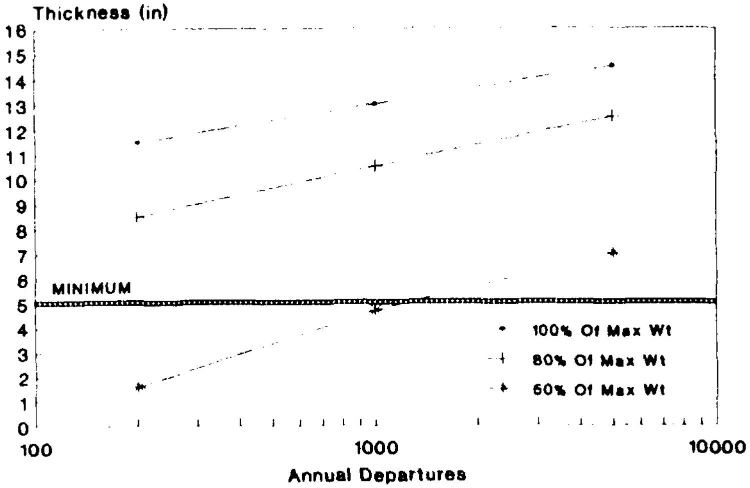
FIGURE 5-11
SENSITIVITY ANALYSIS - DEPARTURES vs. AIRCRAFT WEIGHT

JPCP BONDED OVERLAY
Willard Airport - B-727



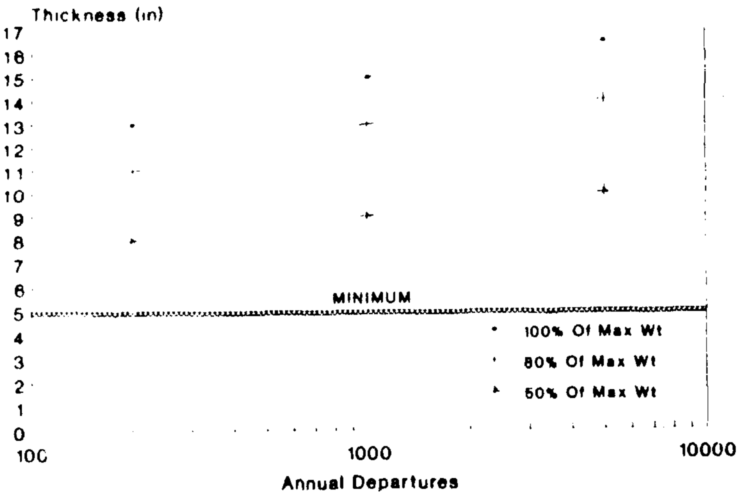
Eo - 6500 ksi Mr - 775 psi Miners - 0.5

JPCP UNBONDED DOWELED OVERLAY
Willard Airport - B-727



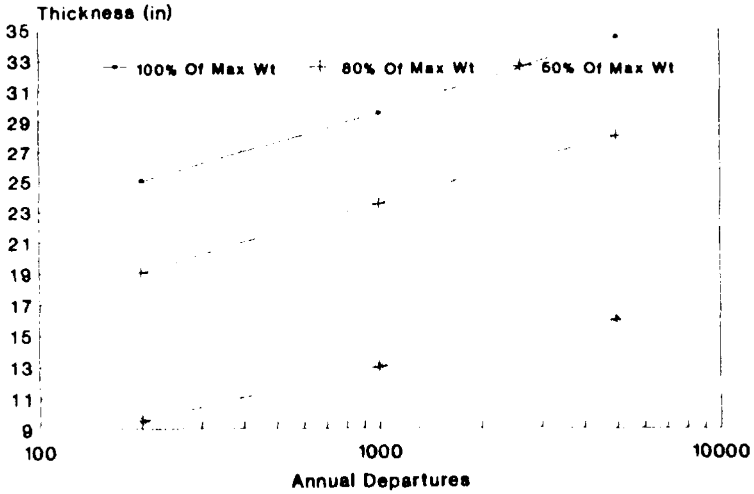
Eo - 6500 ksi Mr - 775 psi Miners - 0.5

JPCP RECONSTRUCTION
Willard Airport - B-727



E - 4000 ksi Mr - 700 psi "k" - 82 pci

ASPHALT OVERLAY
Willard Airport - B-727



Eo - 6500 ksi Mr - 775 psi SCI - 55

1000 and 5000 average annual departures over a 20-year period. The results for an AC overlay show the SCI, rather than past Miner's damage. This is because AIRPACS uses empirical methods for AC overlay design so past Miner's damage has no effect on AC thickness design in AIRPACS.

There are no unusual trends in any of the illustrations in Figure 5-11, but it is interesting to note that a bonded overlay is not much thinner than an unbonded overlay for all variable levels. This due to the poor load transfer across the existing joints. Since dowels cannot be installed in a bonded JPCP overlay, but can be installed in an unbonded JPCP overlay, the benefit of a monolithic slab is almost offset by the increased load transfer that exists with the use of dowels in the unbonded overlay.

5.3.2 Existing JPCP Eo and Mr vs. Aircraft Operational Weight

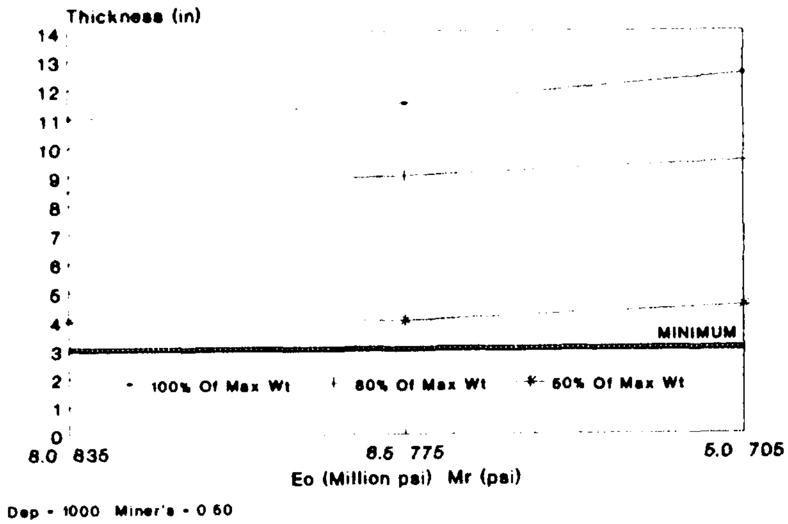
In Figure 5-12, the concrete modulus of elasticity (Ec) and modulus of rupture (Mr) are plotted against thickness for three levels of aircraft weight for the B-727. Eo values that were selected for this analysis ranged from 5 to 8 million psi, which represent a reasonable range of modulus values for existing JPCP pavements. Mr values for each level of Eo were selected using Foxworthy's research results which predict the Mr value (third-point loading) given a backcalculated dynamic Eo [10].

The three curves for the unbonded overlay demonstrate how AIRPACS handles the design when the overlay is not as stiff (Eh^3) as the existing slab, when the overlay is stiffer than the existing slab, and when the overlay is twice as stiff as the existing slab. When the B-727 operates at 50 percent of its maximum weight, the unbonded overlay thickness and corresponding stiffness is never greater than the stiffness of the existing JPC layer. Therefore, since AIRPACS uses the material properties of the existing JPCP in this situation, Eo and Mr of the existing slab will have an effect on the overlay thickness.

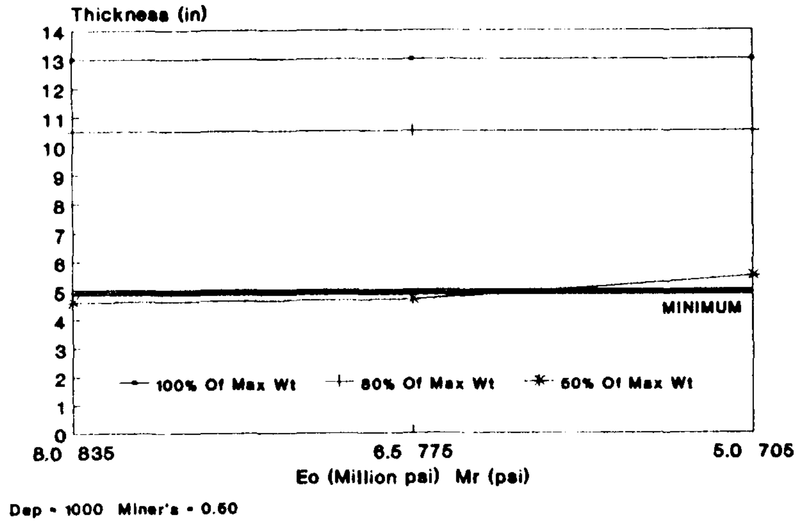
For the remaining two scenarios the unbonded overlay is stiffer than the base slab so AIRPACS uses En and Mr values of the new PCC that are specified by the user. In these instances, the curves for the B-727 operating at 80 and 100 percent of the maximum aircraft weight are straight lines with a slope of zero. Although it is not apparent from the figure, the points on the "100% Of Max Wt" curve were determined by designing the unbonded overlay as a new JPCP pavement on top of a subgrade with a "k" value of 200 psi/in. For this situation, AIRPACS uses this design strategy since an unbonded overlay thickness of 13 inches makes the overlay twice as stiff as the existing JPC layer.

FIGURE 5-12
SENSITIVITY ANALYSIS - Existing JPCP Eo and Mr vs. AIRCRAFT WEIGHT

JPCP BONDED OVERLAY
Willard Airport - B-727

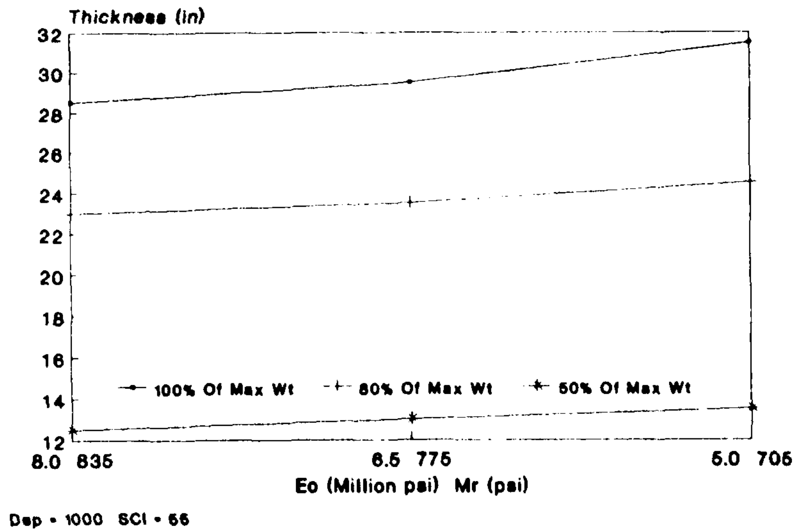


JPCP UNBONDED DOWELED OVERLAY
Willard Airport - B-727



EXISTING Eo AND Mr DO NOT AFFECT RECONSTRUCTION

ASPHALT OVERLAY
Willard Airport - B-727



5.3.3 Past Miner's Damage vs. Aircraft Weight

Figure 5-13 shows the effect of past Miner's damage and the operational weight of the B-727. This figure illustrates some interesting differences between the unbonded and bonded overlay curves. As the past damage approaches one, the JPCP bonded overlay thickness increases to infinity. However, as the past damage and operational weight of the B-727 increase, the JPCP unbonded overlay thickness reaches a maximum thickness of 13 inches since the overlay is designed as a new JPCP layer with a "k" value of 200.

This example illustrates two reasons why one should not install a JPCP bonded overlay on a badly cracked pavement. First, the bonded overlay would perform poorly because of the high amount of reflective cracking that would soon appear in the new overlay. Second, Figure 5-13 shows that if the past damage is greater than 0.75, the bonded overlay will be thicker and more expensive than an unbonded overlay. Figure 5-13 also shows that the amount of preoverlay work that is required to improve the condition of the pavement surface for a bonded overlay, quickly makes a JPCP bonded overlay economically infeasible.

5.3.4 Past Miner's Damage vs. Annual Departures

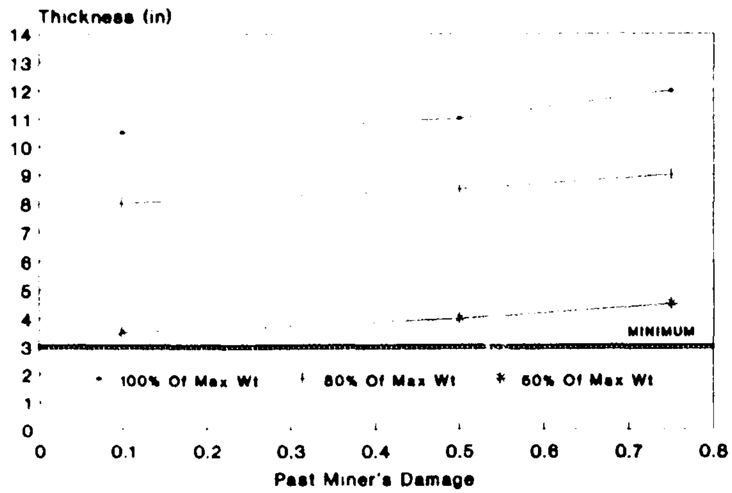
Figure 5-14 shows how the thickness requirement changes for various levels of past Miner's damage and annual departures. For 5000 average annual departures of the B-727 operating at 80 percent of its maximum weight, AIRPACS designs the unbonded overlay as a new JPCP pavement with a "k" value of 200 psi/in (see section 3.2.4.3). This logically supports the trend that is shown in Figure 5-13 for the JPCP unbonded overlay. The rest of the curves shown in this figure do not display any unusual trends that might lead a pavement expert to question the performance of the Designer DPDM in AIRPACS.

5.3.5 Past Miner's Damage vs. Existing JPCP Eo and Mr

Of all the sensitivity analysis figures shown so far, Figure 5-15 clearly shows that past Miner's damage and the modulus of elasticity and modulus of rupture of the existing JPC layer do not impact thickness design as much as aircraft departures and operational weight. This is not surprising since the edge stress will be higher in a stiffer slab assuming that the "k" value is held constant. Therefore, the benefit of a higher modulus of rupture for the stiffer slab is partially offset by the higher edge stress in the slab.

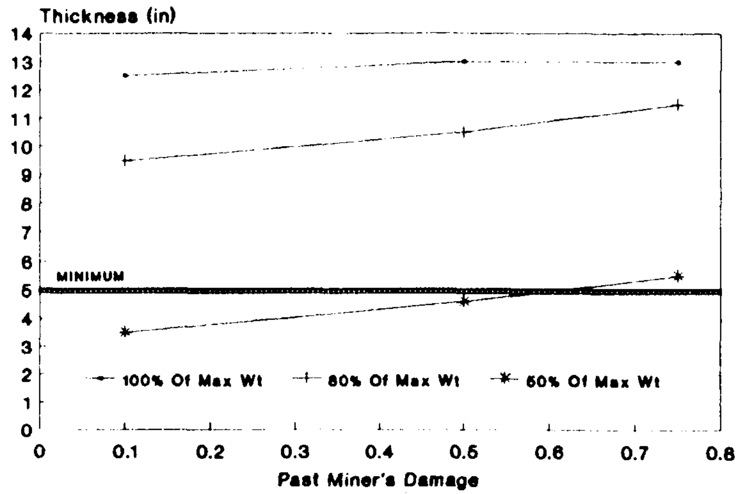
FIGURE 5-13
SENSITIVITY ANALYSIS - PAST MINER'S DAMAGE vs. AIRCRAFT WEIGHT

JPCP BONDED OVERLAY
Willard Airport - B-727



Eo = 8000 ksi Mr = 836 psi Dep = 1000

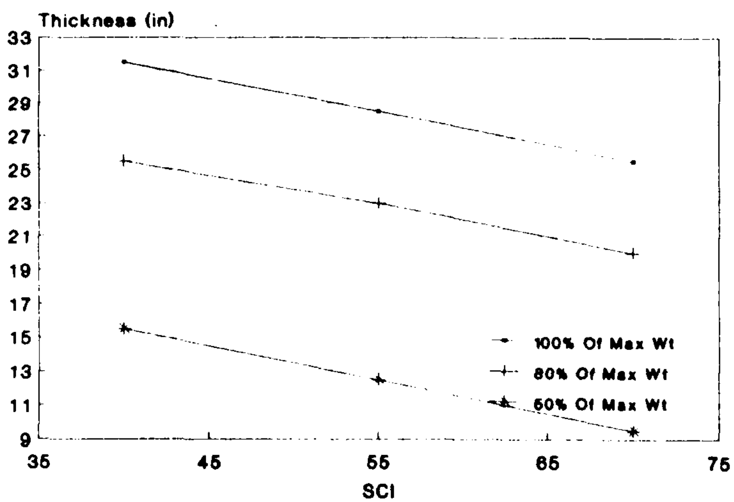
JPCP UNBONDED DOWELED OVERLAY
Willard Airport - B-727



Eo = 8000 ksi Mr = 836 psi Dep = 1000

PAST MINER'S DAMAGE
DOES NOT AFFECT RECONSTRUCTION

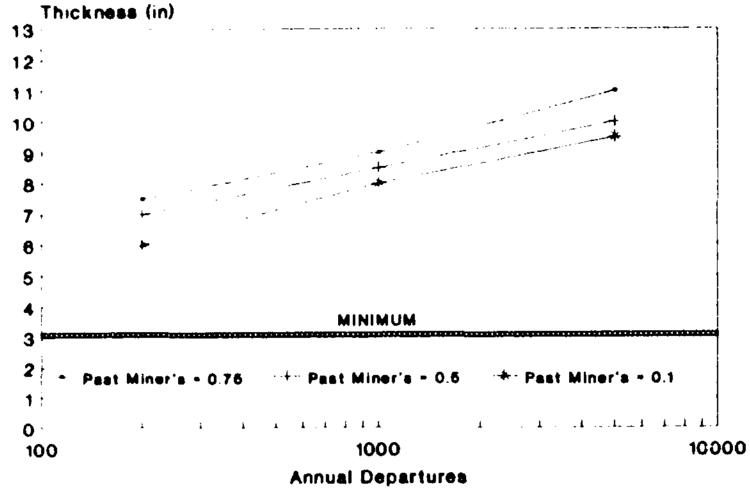
ASPHALT OVERLAY
Willard Airport - B-727



Eo = 8000 ksi Mr = 836 psi Dep = 1000

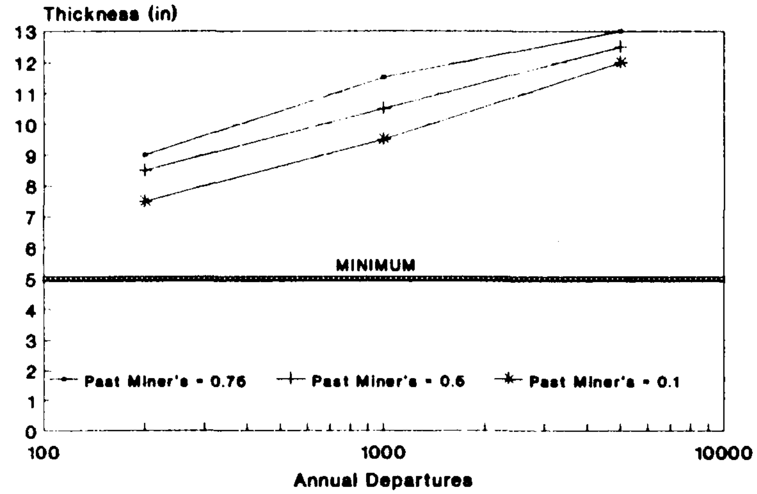
FIGURE 5-14
SENSITIVITY ANALYSIS - PAST MINER'S DAMAGE vs. ANNUAL DEPARTURES

JPCP BONDED OVERLAY
Willard Airport - B-727



Eo = 8000 ksi Mr = 836 psi Op Wt = 80%

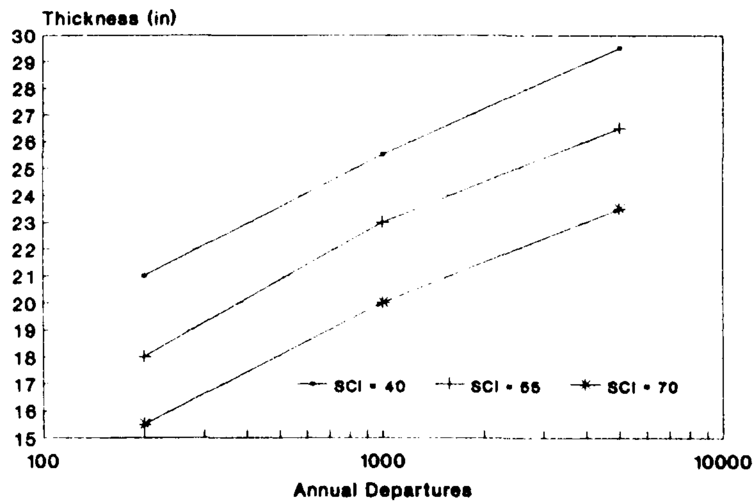
JPCP UNBONDED DOWELED OVERLAY
Willard Airport - B-727



Eo = 8000 ksi Mr = 836 psi Op Wt = 80%

PAST MINER'S DAMAGE
DOES NOT AFFECT RECONSTRUCTION

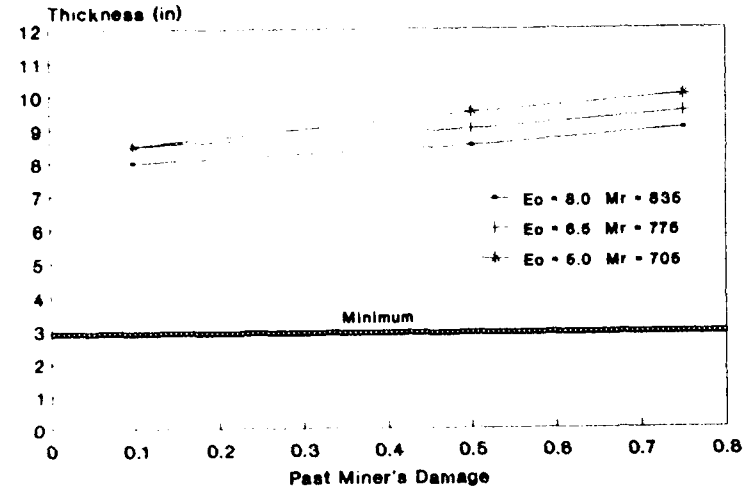
ASPHALT OVERLAY
Willard Airport - B-727



Eo = 8000 ksi Mr = 836 psi Op Wt = 80%

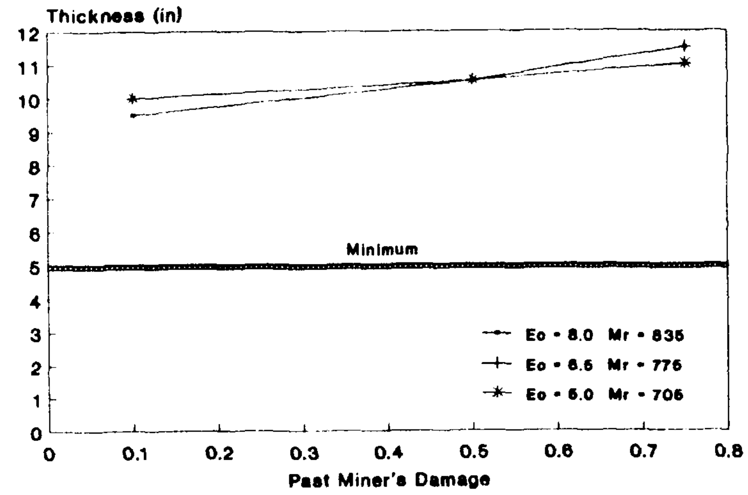
FIGURE 5-15
SENSITIVITY ANALYSIS - PAST MINER'S DAMAGE vs. Existing JPCP Eo and Mr

JPCP BONDED OVERLAY
Willard Airport - B-727



Op Wt = 80% Dep = 1000

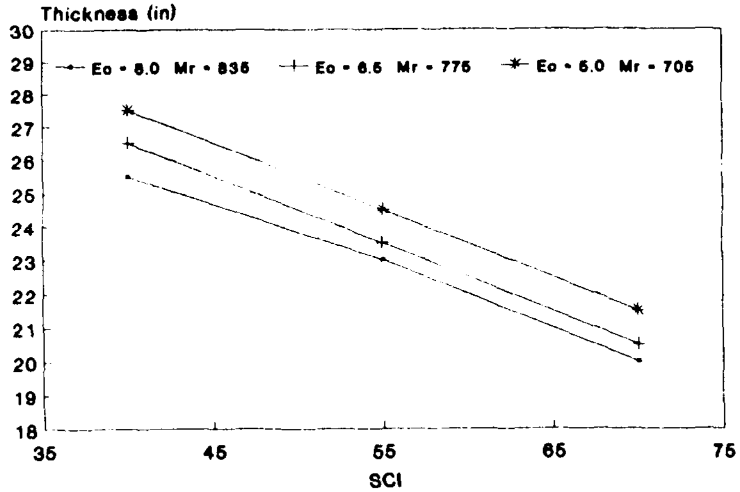
JPCP UNBONDED DOWELED OVERLAY
Willard Airport - B-727



Op Wt = 80% Dep = 1000

NEITHER FACTOR AFFECTS RECONSTRUCTION

ASPHALT OVERLAY
Willard Airport - B-727



Op Wt = 80% Dep = 1000

Figure 5-15 illustrates an inconsistency that may arise when using the current JPCP unbonded overlay design procedure in AIRPACS. When the past Miner's damage is 0.75, this figure shows that a thinner unbonded overlay is permitted for a JPCP with an Eo value of 5 million psi than with an Eo value of 6.5 or 8 million psi. This occurs because the unbonded overlay may be twice as stiff as the existing JPC layer if the old pavement has a low Eo value, but it may not be twice as stiff if the existing Eo value is slightly higher.

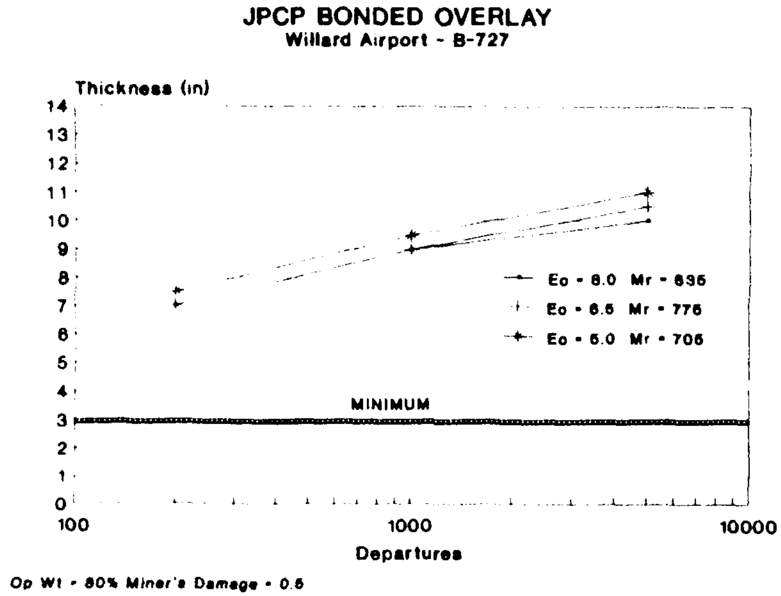
For this example, the unbonded overlay is twice as stiff as the base JPC layer when its modulus is 5 million psi and the overlay is 11 inches thick (past Miner's damage = 0.75). However, if the existing JPC layer modulus is 6.5 or 8 million psi, an 11-inch overlay will not be twice as stiff as the existing JPC layer. Therefore, AIRPACS designs the overlay as a new JPC pavement with a "k" value of 200 psi/in (see section 3.2.4.3) if the modulus is 5 million psi. But when the modulus is 6.5 or 8 million psi, AIRPACS uses both mechanistic and heuristic knowledge to determine the unbonded overlay thickness

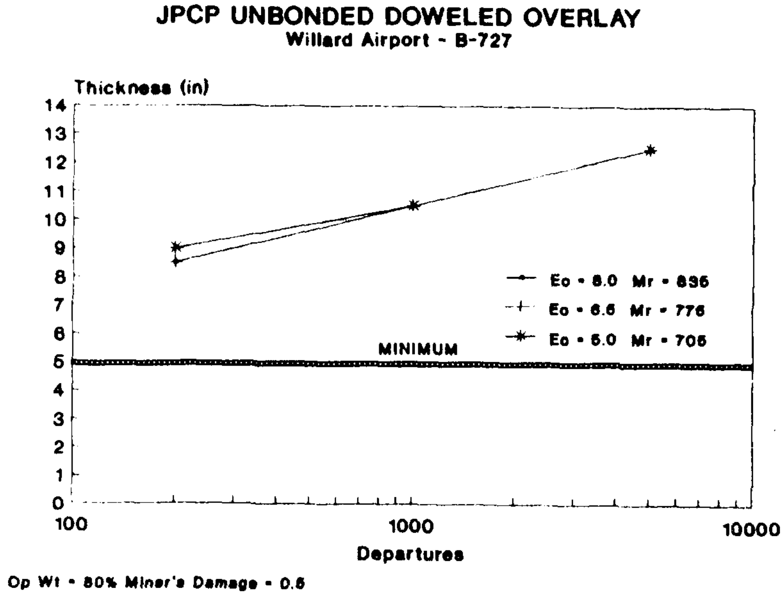
5.3.6 Departures vs. Existing JPCP Eo and Mr

Figure 5-16 also shows that a 60 percent increase in the concrete modulus of elasticity and a corresponding 18 percent increase in the modulus of rupture have a relatively small effect on the overlay thicknesses. For a bonded overlay, the thickness increase ranges from 7 percent for 200 departures to 10 percent for 5000 annual departures of a B-727. If an AC overlay is placed, the thickness increase is approximately 10 percent. Figure 5-16 also shows that the existing PCC modulus of rupture and modulus of elasticity have little effect on the unbonded overlay thickness.

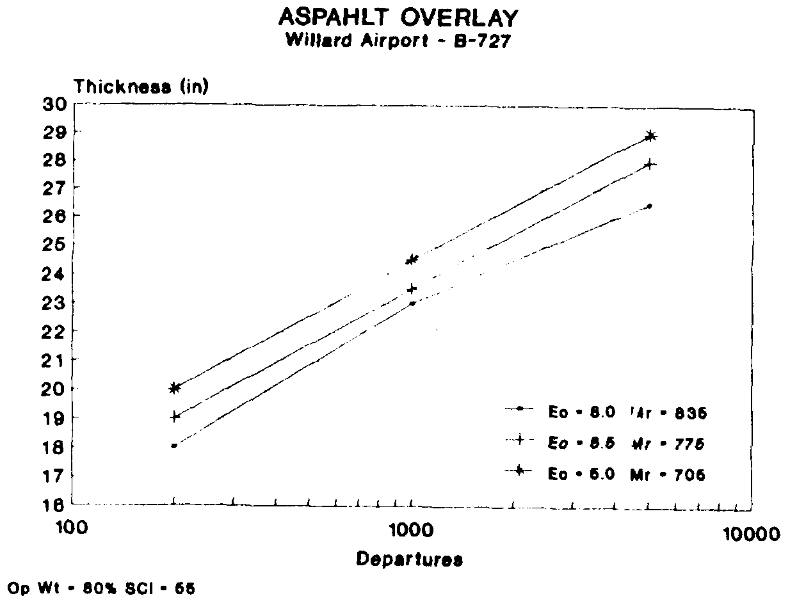
When the number of aircraft departures reaches 1000, the JPCP unbonded overlay thickness increases to the point where the overlay is stiffer than the existing JPC layer for all existing layer modulus values. At this point, AIRPACS uses the new PCC material properties specified by the user. Therefore, as the number of departures increases further, the existing JPC layer modulus obviously has no effect on the thickness design.

FIGURE 5-16
SENSITIVITY ANALYSIS - DEPARTURES vs. Existing JPCP Eo and Mr





EXISTING Eo AND Mr DO NOT AFFECT RECONSTRUCTION



5.4 TEST SUMMARY

AIRPACS performance and reliability were tested using consultant reports which were prepared for airports in different climatic regions of the United States. The tests show that AIRPACS frequently agrees with the types of JPCP rehabilitation alternatives that the consultant investigated in detail. AIRPACS may investigate more types of alternatives, but the PCI forecast and economic analysis of all alternatives analyzed by the Designer DPDM often leads the user to select the same alternative as the consultant.

AIRPACS design thickness and joint spacing recommendations were compared to the consultant's recommendations. The consultant's recommendations were based on mechanistic design procedures that were compared to FAA or AFM 88-6 design procedures for structural overlays or reconstruction. AIRPACS inputs were kept the same as the consultant's inputs so that feasibility studies and design output comparisons would be meaningful. Although the thickness and joint spacing recommendations of AIRPACS are reasonable, there are instances for which the outputs differ with the consultant's recommendations. When structural improvements are required, the output differences occur most frequently in the design of an unbonded overlay.

The sensitivity analysis shows how the thickness of a structural alternative changes for different levels of aircraft traffic, aircraft operational weight, existing JPC layer Eo and Mr, and past Miner's damage. It should not be surprising to see that aircraft departures and aircraft operational weight have the most significant impact on structural thickness designs. However, it is surprising to see that changes in Eo, Mr, and past Miner's damage do not significantly change structural thickness requirements.

For most variable input changes, the analysis demonstrates that AIRPACS outputs can be theoretically justified. The exception is the unbonded overlay design procedure, which can be enhanced in the future. Despite the problem that was noted earlier in this chapter, the unbonded overlay design approach used in AIRPACS is believed to have more merit than the approach used in the FAA or AFM 88-6 design procedures. The heuristics that are used in these unbonded overlay design procedures are too simple for such complicated pavement behavior. This philosophy is supported by the validation tests that were conducted for the Grand Forks AFB runway. For several of these sections, the AFM 88-6 unbonded overlay design procedure failed to recognize any structural overlay requirement.

CHAPTER 6

CONCLUSIONS

The purpose of this chapter is to summarize the research work, identify significant original contributions of this work, current limitations of the implementation of a knowledge-based approach to airfield pavement rehabilitation design, and discuss future improvements and work in this research area.

6.1 SUMMARY

This research uses a knowledge-based approach to perform rehabilitation designs for airport jointed plain concrete pavements (JPCP). A Blackboard architecture is used to represent the knowledge of planners, constructors, airfield managers and designers who are involved in the rehabilitation design process. The knowledge of each design process decision maker (DPDM) is represented in separate knowledge-bases, which is one of the key characteristics of the Blackboard architecture [25].

Each decision maker involved in the JPCP rehabilitation design process uses its problem-solving knowledge and airport information to make a contribution to the design process. The problem-solving knowledge of each DPDM is represented using rules and a forward-chaining inference strategy. Airport information is represented using a collection of objects to describe the airport pavement system.

Airport objects have been grouped into classes such as aircraft, JPCP components, JPCP distresses, climate regions and JPCP repairs. All objects within these classes contain information which describes inherent attributes of the object as well as interrelationships among objects within the airport environment. This natural representation of the airport environment makes it easy to understand the rules in each of the knowledge-bases which represent an expert's problem-solving knowledge.

A collection of objects is also used to represent analytical tools that an expert uses to solve rehabilitation design problems. A designer may use models to calculate slab edge stresses, deflection load transfer efficiencies, stress load transfer efficiencies and allowable aircraft coverages. Likewise, JPCP performance prediction and economic analysis work can be efficiently handled using object-oriented programming.

These knowledge representation techniques were used to implement an AIRfield PAvement Consultant System (AIRPACS) using Goldhill Computer's "Goldworks II" expert system shell. Goldworks II and Microsoft Windows were also used to create an user interface for AIRPACS. This allows the user to quickly enter airport information which AIRPACS uses to select feasible rehabilitation alternatives for a specific area, or feature, of a runway, taxiway or apron.

Routine maintenance, restoration, safety enhancing overlays and structural improvements are considered in the initial feasibility study. If a structural improvement is required, AIRPACS reviews pavement evaluation data and the airport environment to decide if reconstruction, or one of several overlay types, is feasible. Mechanistic, heuristic and empirical design methods are then used to select a reconstructed JPCP thickness, JPCP or asphalt concrete overlay thickness, joint types, joint load transfer efficiencies and joint spacings.

The reliability of AIRPACS recommendations were compared to recommendations made by a pavement consultant firm for several projects. Consultant reports that were used in the validation process included airfields that are located in several climatic regions of the United States. These reports use a mechanistic design approach but always compare the results to Air Force Manual 88-6 or the Federal Aviation Administration design procedures. Although all expert systems must be continually updated and enhanced, this research demonstrated that AIRPACS is a very powerful design tool that can quickly provide reasonable design solutions for JPCP rehabilitation in the airport environment.

6.2 RESEARCH CONTRIBUTIONS

The airport pavement knowledge acquired during this research can be used to quickly solve difficult JPCP rehabilitation designs for an airport. For structural thickness designs, the latest design technology is used to improve the design procedures that are used by the FAA, the U.S. Air Force, and pavement engineering consultants. A Blackboard architecture is used to incorporate several knowledge-bases that must be used to select feasible alternatives during the planning stage, consider constructor concerns and capabilities, consider the airfield manager's concerns, perform traditional structural designs, predict the performance of designed alternatives and perform economic analyses. For the first time in airport pavement design history, enough knowledge has been acquired and integrated in the form of knowledge bases to solve difficult airfield pavement rehabilitation design problems.

Although a knowledge-based approach is a very powerful design approach, the power and flexibility of this approach is further enhanced when it is complemented with object oriented programming. Collections of objects have been used in this research to develop a data structure which naturally describes an airport environment. This data structure describes the hierarchical relationship among elements in the airport environment and provides the framework for future expansions in airport pavement rehabilitation.

Collections of objects have also been used to describe performance, economic models and pavement behavior. Pavement behavior information could have been retrieved through external calls to other programs such as finite element or elastic layer programs, but this would increase the time required to solve a problem. Although experts frequently use these programs to compute stresses, deflections and strains, the author wanted to advance the current state of JPCP thickness design by using new concepts (i.e. ESWR) in the area of structural analysis.

Since AIRPACS makes no calls to external programs, equations were developed for several aircraft to estimate the equivalent single wheel radius (ESWR) when a multi-wheel gear is placed on a transverse joint. These equations and Westergaard's edge stress equation for a single load can then be used to predict the free edge stress for any multi-wheel gear aircraft. Once these free edge stresses are determined, the Designer DPDM uses procedures that have not been used by the FAA, AFM 88-6 and most pavement consultants.

In the structural design, AIRPACS considers four periods of the year to account for seasonal temperature changes. If the transverse joints are not doweled, AIRPACS uses four deflection load transfer efficiencies (DLTE) for each of the seasons. For each aircraft that uses the pavement facility, AIRPACS selects one of four possible DLTE versus stress load transfer efficiency (SLTE) curves. In the past, most consultants have used one DLTE and one DLTE versus SLTE curve to calculate the edge stress in a JPC pavement.

AIRPACS also handles mixed aircraft design differently than the FAA or AFM 88-6 design procedure. Future fatigue damage is estimated for each aircraft that will operate on the pavement facility. Once this is completed, a critical aircraft is selected based on the future damage it will cause in the JPCP. Gear spacings and pass-to-coverage ratio concepts are then used to account for the contributions of all aircraft to the cumulative fatigue damage at the critical gear's location.

Another unique contribution of this research is the application of object-oriented programming to perform rehabilitation designs for multiple JPCP sections of several pavement facilities on an airfield. Once an AIRPACS user creates an airfield pavement description and enters all data for these objects, the user can have AIRPACS design one or more JPCP sections of one or more pavement facilities. The ability of the AIRPACS knowledge-bases to make decisions about more than one section at a time illustrates the power and flexibility of a combining a heuristic rule-based system with an object-oriented programming environment.

Finally, this research has introduced another use for the data collected during a pavement condition survey. Presently, this data is used to compute the pavement condition index (PCI) and the structural condition index (SCI) of a JPCP section. This research proposes using survey data to compute a FOD condition index (FCI). The amount of debris on an airfield pavement is a key safety issue and must be considered in the rehabilitation design process. AIRPACS uses the FCI to study FOD potential during the planning stage of the design process.

6.3 SHORTCOMINGS

AIRPACS has several limitations that should be corrected before future expansions are made to the knowledge-based system. These limitations include inputs to the airfield database as well as assumptions that are made by the Designer DPDM.

One of the concerns during data entry is the accuracy of the equations which AIRPACS uses to predict the deduct value for a JPCP distress. The problem occurs when the quantity of a distress is very low (i.e. less than 1%). The current equations often overestimate the deduct value in these situations. If there are several small quantities of the JPCP section distresses, AIRPACS may significantly underestimate the PCI value. Therefore, the equations which model the deduct curves in the PCI manuals [31, 32] should be improved.

One of the shortcomings of the Designer DPDM knowledge-base is its inability to identify those situations where the longitudinal joint is the critical joint in a structural thickness design. Although transverse joint loading is the critical loading location for a majority of the time, the Designer DPDM should be able to determine free edge stresses at the longitudinal joint if that joint is the critical joint. This would entail developing another set of ESWR equations for each aircraft when its gear is placed at the longitudinal edge of the slab. Since longitudinal joint spacings depend on the radius of relative stiffness, P/C ratios would have to be calculated for each aircraft for a range of joint spacings. In addition, the Designer knowledge-base will have to be modified so that the longitudinal joint is always checked during a structural design.

Another limitation of the Designer DPDM is the programming inefficiency currently built into the thickness design calculations. Numerical calculations are often duplicated during the Designer DPDM's work. For example, when reconstruction and an AC overlay are both feasible structural alternatives for a section, AIRPACS creates an object for each of these rehabilitation alternatives. When the Designer DPDM makes its contribution to the design process, it determines the new JPC layer thickness twice, once for the reconstruction alternative and once for the asphalt overlay alternative.

This inefficiency is further amplified if AIRPACS is designing several JPCP sections. If reconstruction and an AC overlay are feasible for each of these sections, the Designer DPDM must currently repeat its structural thickness design tasks several times. In reality, the Designer DPDM may have to perform these tasks only once for this scenario if design inputs are the same. Future improvements to AIRPACS should increase the intelligence of the Designer DPDM so it recognizes scenarios where it can save time by not repeating tasks.

Another area for improvement in the Designer DPDM is the method of selecting joint spacing recommendations. AIRPACS currently uses the radius of relative stiffness, ℓ, and the existing dimensions of the JPCP section to select longitudinal and transverse joint spacings. However, if several adjacent sections are being designed, the Designer DPDM should consider the dimensions of the section group rather than an individual section. Validation tests show that this is a very important consideration if keel, edge and full-facility width sections are included in the design. Since longitudinal joint spacing may be very sensitive to the width of the section or pavement facility, the facility width should be used if improvements are required for edge and keel sections.

Validation tests also raise serious concerns about the capability of Goldworks II to handle the size of a database that would represent a typical airport or airfield. During validation testing, the size of the data file for an airfield had to be limited to four JPCP sections. When the number of sections is increased beyond this point, Goldworks II performs very sluggishly.

6.4 FUTURE RESEARCH

The Blackboard architecture and knowledge-based design approach used in this research demonstrate that this technology can be applied to rehabilitation designs of airfield pavements. This research used this design approach for rehabilitation of JPCP pavements that currently have no existing overlays. However, there is no evidence that suggests this approach could not be used to create new knowledge-bases and expand the existing knowledge-bases in AIRPACS to perform pavement evaluation and rehabilitation design for other types of airfield pavements.

Currently, the user must input JPCP evaluation results before AIRPACS can begin the rehabilitation design process. Structural, frost, drainage, deterioration, joint, roughness and skid evaluation models should be developed and integrated with the current knowledge-bases in AIRPACS. If this work is completed in the future, a less experienced pavements engineer could use AIRPACS because the system would not be relying on the user to make critical decisions when evaluation results are not available.

The airfield pavement system descriptions (APSD) and existing knowledge-bases in AIRPACS should be expanded to include other types of airfield pavements. Specifically, future work should include asphalt concrete (AC) pavement, jointed reinforced concrete pavement (JRCP), continuously reinforced concrete pavement (CRCP), and composite pavements (PCC pavements constructed or overlaid with AC surfaces). Since the Blackboard architecture and object-oriented structure is defined for a JPC pavement, the airfield pavement system descriptions and the knowledge-bases can readily accommodate the remaining types of airfield pavements.

Another enhancement that should be made is to improve the method of considering preoverlay repair for JPCP pavements and other types of pavements added in the future. Currently, AIRPACS users must enter all section data twice if they want to consider the effect of preoverlay repair. The second time the user enters the data, the PCI distress quantities entered for the JPCP section are for those distresses that would be present after preoverlay repair.

The effect of preoverlay repair could be automated by allowing the user to select a certain level of repair. AIRPACS already identifies five levels of repair so the user could select no preoverlay repair, emergency repairs, critical repairs, complete maintenance or restoration to be used for preoverlay repair work. In addition, the user should be allowed to select different levels of repair for each type of rehabilitation overlay and for each section when multiple sections are being designed. The level of repair would affect alternative feasibility and would make a difference in the work output of the Economist DPDM.

The first enhancements that are make to AIRPACS should be include preoverlay in AIRPACS and the addition of the Economist DPDM knowledge-base in AIRPACS. The work of the Economist was validated using the output from the Designer DPDM in AIRPACS and a Lotus 1-2-3 spreadsheet. When the Economist calculates the EUAC and PCI performance cost for a structural or safety enhancing overlay, it will have to include preoverlay costs that will be related to the level of preoverlay repair.

Another enhancement that can be made to AIRPACS is the addition of the Forecaster knowledge-base. The PCI performance prediction model discussed in section 3.1.6 can easily be added to AIRPACS. In addition to this knowledge, the Forecaster DPDM should have the capability to estimate the area under the PCI vs. time curve when repairs are made at periodic intervals during the design life of the pavement. This would enhance the PCI prediction obtained by using equation 3.12 because this equation cannot directly consider the effect of various levels of repair that are made throughout the design life of a pavement section.

Finally, explanation and help facilities should be added to the existing AIRPACS user interface. These facilities were not included in the prototype of AIRPACS since they were not required for validation tests. Goldworks II already has a built-in explanation facility which could be used as an interim solution, but the explanations could be improved to make them more user friendly.

APPENDIX A

FEDERAL AVIATION ADMINISTRATION (FAA) PUBLICATIONS LIST

FAA PUBLICATIONS

A. AC-00-2, Federal Register, Advisory Circular Checklist and Status of Federal Aviation Regulations.

B. AC 150/5320-12, Methods for the Design, Construction, and Maintenance of Skid Resistant Airport Pavement Surfaces.

C. AC 150/5325-2, Airport Design Standards - Airports Served by Air Carriers - Surface Gradient and Line-of-Sight.

D. AC 150/5325-5C, Aircraft Data

E. AC 150/5325-6, Airport Design Standards - Effects and Treatment of Jet Blast.

F. AC 150/5335-1, Airport Design Standards - Airports Served by Air Carriers - Taxiways.

G. AC 150/5335-2, Airport Aprons

H. AC 150/5335-4, Airport Design Standards - Airports Served by Air Carriers - Runway Geometrics.

I. AC 150/5370-11, Use of Nondestructive Testing Devices in the Evaluation of Airport Pavements.

J. AC 150/5320-5B, Airport Drainage, dated July 1, 1970.

K. AC 150/5370-10, Standards for Specifying Construction of Airports, dated October 24, 1974.

L. FAA-RD-73-169, Review of Soil Classification Systems Applicable to Airport Pavement Design, May 1974, by Yoder AD-783-190.

M. FAA-RD-74-30, Design of Civil Airfield Pavement for Seasonal Frost and Permafrost Conditions, October 1974, by Berg ADA-006-284.

N. FAA-RD-74-36, Field Survey and Analysis of Aircraft Distribution on Airport Pavements, February 1975, by Ho Sang ADA-011-488.

O. FAA-RD-76-66, Design and Construction of Airport Pavements on Expansive Soils, January 1976, by McKeen ADA-28-094.

P. FAA-RD-73-198-I, Design and Construction and Behavior Under Traffic of Pavement Test Sections, June 1974, by Burns, Rone, Brabston, Ulery, AD-785-024.

Q. FAA-RD-74-33-III, Design Manual For Continuously Reinforced Concrete Pavements, May 1974, by Treybig, McCullough, Hudson, AD-780-512.

R. FAA-RD-75-110-II, Methodology for Determining, Isolating and Correcting Runway Roughness, June 1977, by Seeman, Nielsen, ADA-44-378.

S. FAA-RD-73-198-III, Design and Construction of MESL, December 1974 by Hammitt, AD-005-893.

T. FAA-RD-76-179, Structural Design of Pavements for Light Aircraft, December 1976, by Ladd, Parker, Percira, ADA-041-300.

U. FAA-RD-74-39, Pavement Response to Aircraft Dynamic Loads, Volume II - Presentation and Analysis of Data, by Ledbetter, ADA-22-806.

APPENDIX B

EQUIVALENT SINGLE WHEEL RADIUS (ESWR) EQUATION VALIDATION RESULTS

ESWR VALIDATION RESULTS

The ESWR validation results presented in this appendix show that the equivalent single wheel radius can be used to quickly and accurately determine the free edge stress at the transverse joint. Once the ESWR is calculated for an aircraft for a specific JPCP system, Westergaard's equation for a single load can be used to calculate the free edge stress. The validation results show that this method performs as well as the equations developed by the U.S. Army Corps of Engineers.

These validation results also raise serious questions about the methods used by the FAA and U.S Air Force to determine the equivalent number of departures of the critical aircraft in a mixed aircraft design. The ESWR vs. radius of relative stiffness, ℓ, curves in this appendix clearly show that the type of aircraft gear should not be used to convert the departures of an aircraft to an equivalent number of departures of the critical aircraft.

Since the ESWR is a direct indicator of the amount of concrete fatigue damage an aircraft imparts to the pavement, those aircraft with similar ESWR vs. ℓ curves will cause similar amounts of damage when the gear loads are similar. These curves show that aircraft with the same type of main gear may cause very different amounts of damage. In addition, aircraft with different types of main gear may cause similar amounts of damage (i.e. C-130 and B-727).

The current methods of converting aircraft to a critical aircraft also do not consider the difference in main gear spacing. If the gear spacing difference is significant, the non-critical aircraft should not be considered since the pass-to-coverage ratio will be very high at the critical aircraft gear location. Finally, the channelized and unchannelized pass-to-coverage ratios of non-critical aircraft may be very different than the critical aircraft's P/C ratios. These issues suggest that improvements should be made in the current methods of performing mixed aircraft traffic design.

FIGURE B-1
ESWR COMPARISON OF AIRCRAFT WITH TWIN TANDEM MAIN GEAR

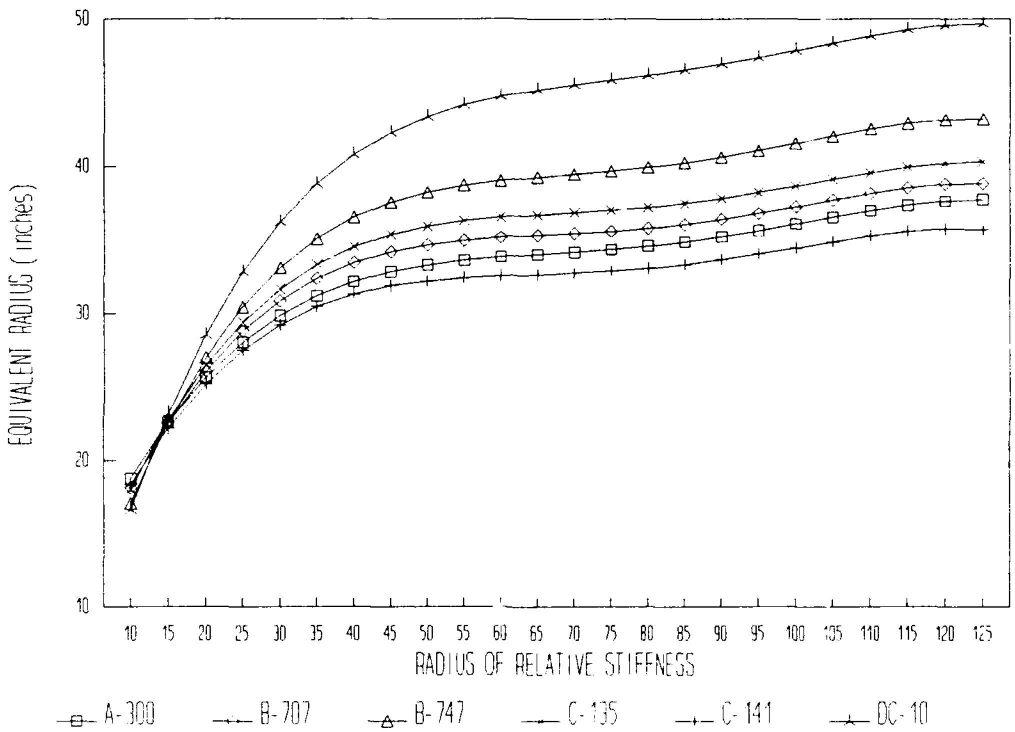


FIGURE B-2
FREE EDGE STRESS OF A 15 INCH JPCP WHEN LOADED BY A C-141 AIRCRAFT

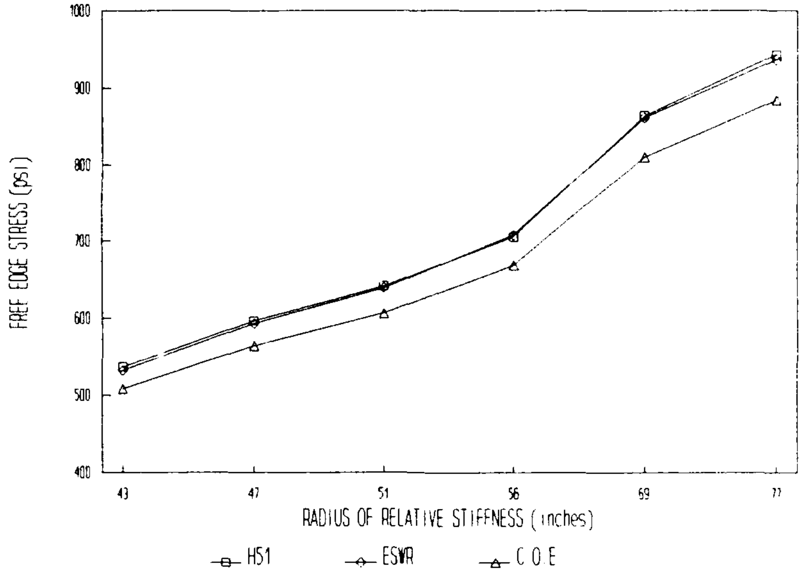


FIGURE B-3
FREE EDGE STRESS OF A 15 INCH JPCP WHEN LOADED BY A B-747 AIRCRAFT

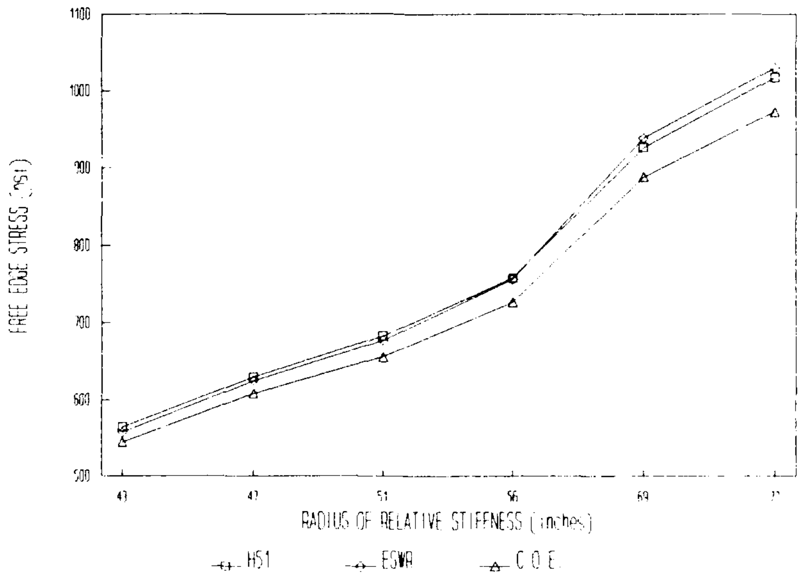


FIGURE B-4
ESWR COMPARISON OF AIRCRAFT WITH TWIN MAIN GEAR

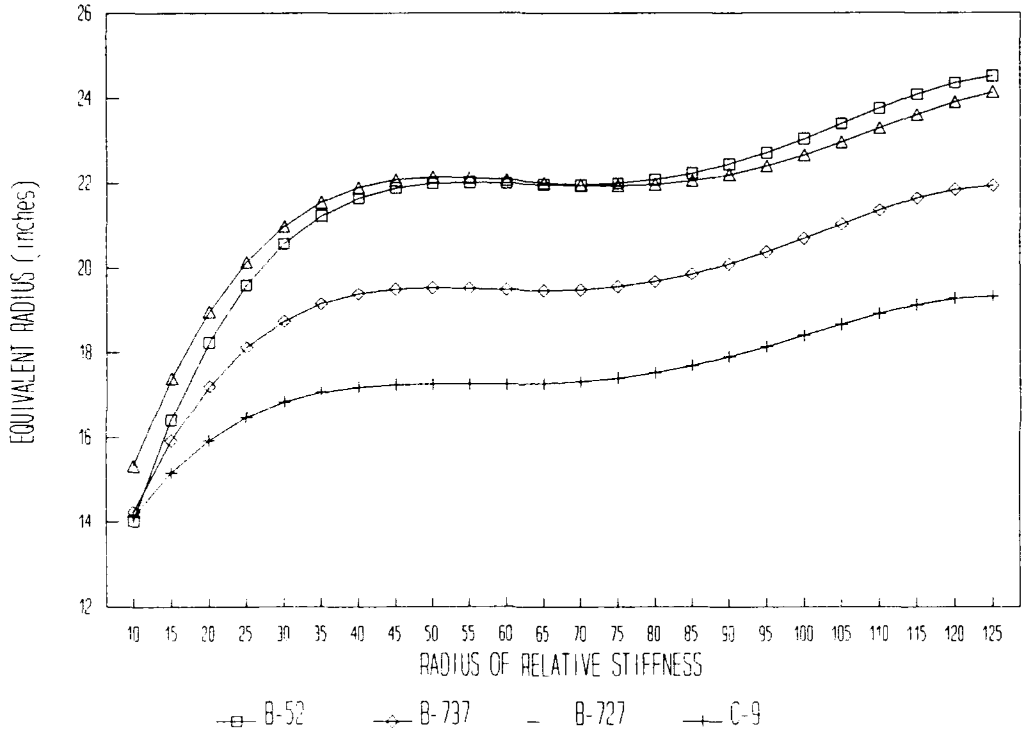


FIGURE B-5
FREE EDGE STRESS OF A 15 INCH JPCP WHEN LOADED BY A B-727 AIRCRAFT

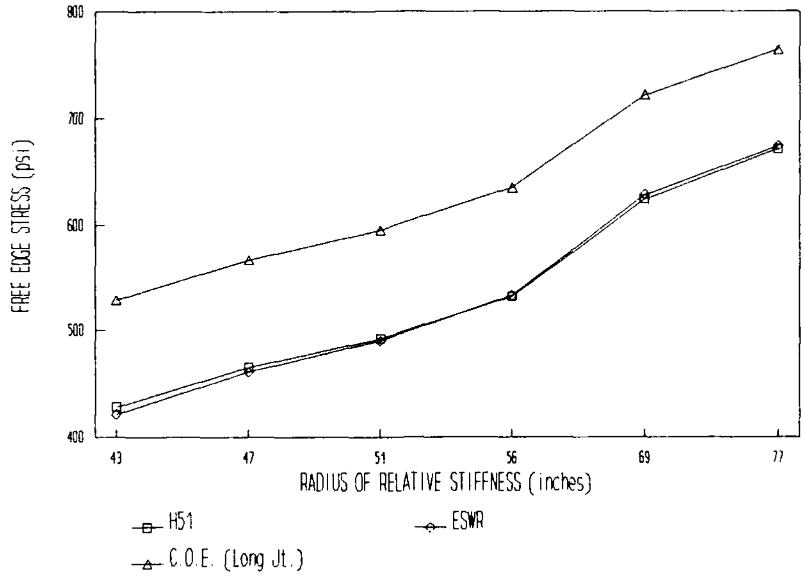


FIGURE B-6
FREE EDGE STRESS OF A 15 INCH JPCP WHEN LOADED BY A B-737 AIRCRAFT

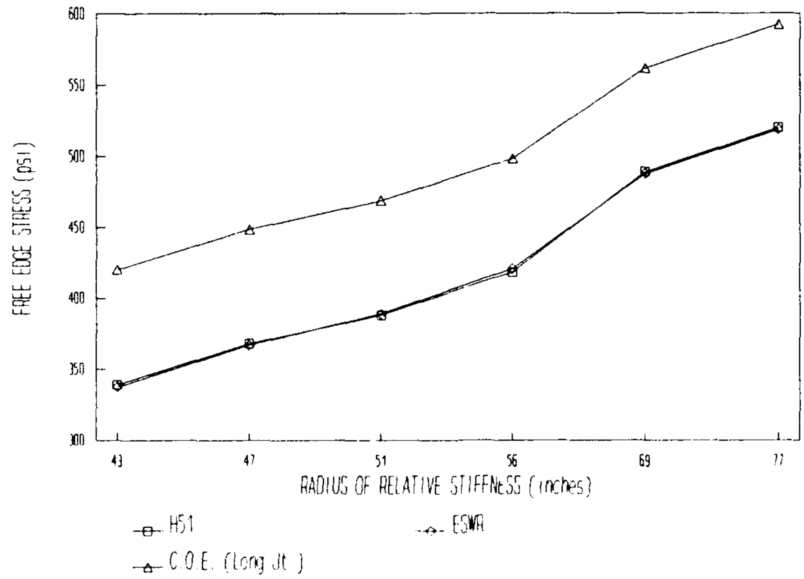


FIGURE B-7
ESWR COMPARISON OF AIRCRAFT WITH DIFFERENT TYPES OF MAIN GEAR

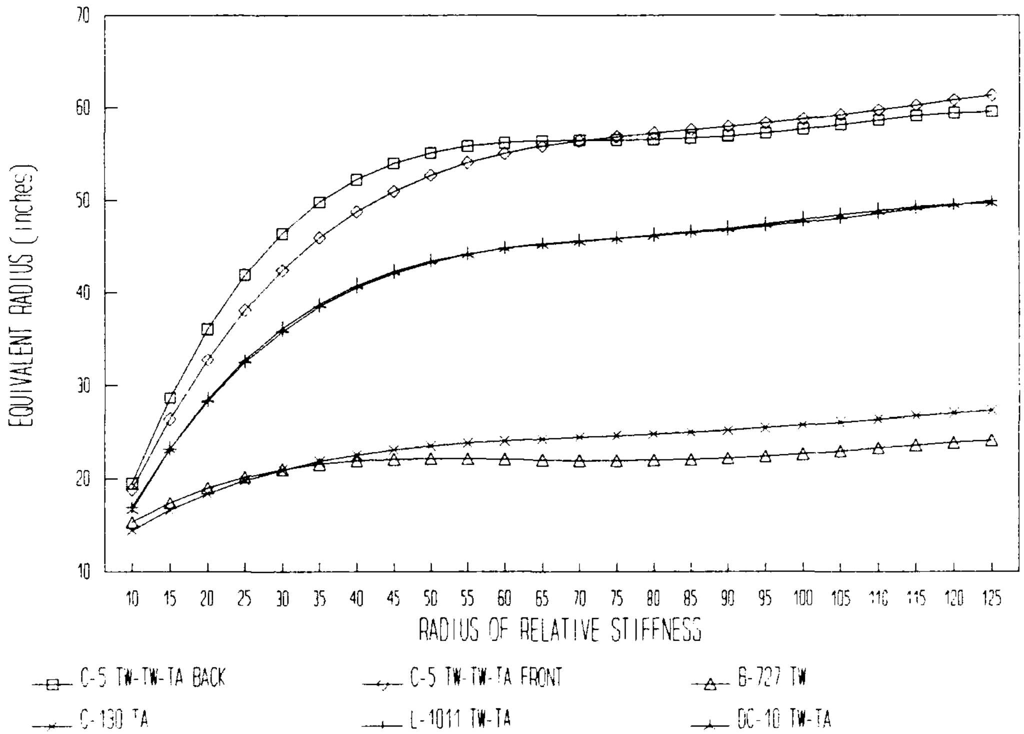


FIGURE B-8
FREE EDGE STRESS OF A 15 INCH JPCP WHEN LOADED BY A C-5 AIRCRAFT

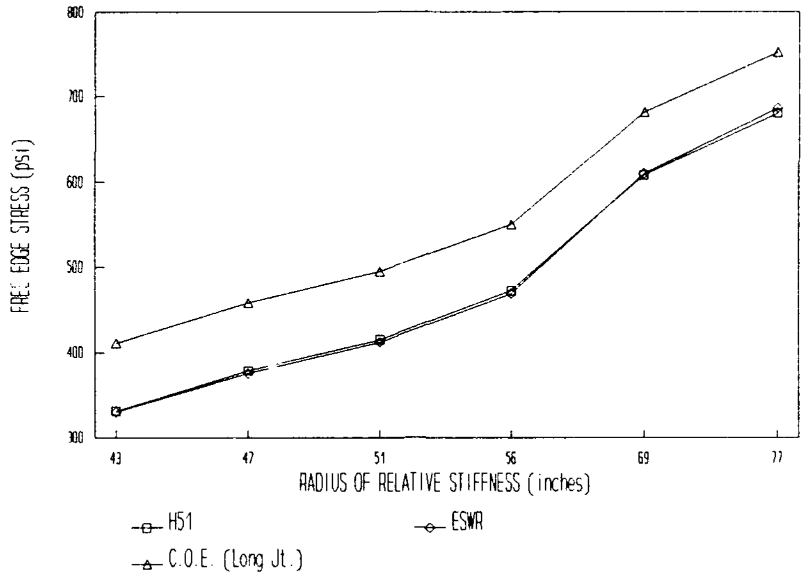
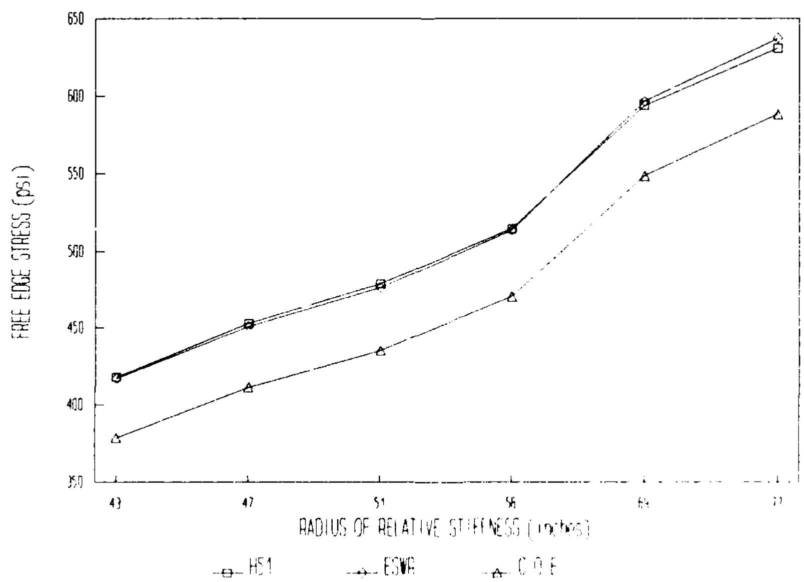


FIGURE B-9
FREE EDGE STRESS OF A 15 INCH JPCP WHEN LOADED BY A C-130 AIRCRAFT



APPENDIX C

BIOGRAPHICAL DATA OF AIRPACS EXPERTS

KNOWLEDGE ACQUISITION AND EXPERT BIOGRAPHICAL DATA

Planner knowledge in AIRPACS was acquired primarily through structured interviews with U.S. Air Force MAJCOM pavement engineers and engineers from the U.S. Army Corps of Engineers. This appendix contains the interview schedule and a condensed biography of each person interviewed during the trip. Several observations about the knowledge acquisition interviews are worth noting at this point, in the hope that these observations might aid others who are involved in knowledge acquisition.

All experts interviewed during the knowledge acquisition trip were very familiar with PAVER. Those experts who participated in the development of the PCI and PAVER were receptive to the idea of a KBES and recognized it as a potentially powerful tool which could be built using many existing PCI and PAVER concepts. Since the author is a knowledge engineer who has a considerable amount of pavement experience, there was no need for domain familiarization. This situation expedited the knowledge acquisition process since structured interviews could be used to help both parties quickly focus on key planning issues.

Despite the knowledge level of all parties in the interview, a brief overview of the planning process served as an "ice breaker" and allowed the knowledge engineer to transition to the structured portion of the interview. The "ice breaker" session also helped the expert get comfortable with the interview environment and a tape recorder which was used during all interviews. Tape recording the interview was a good knowledge acquisition technique since the interviews could be reviewed while traveling between interview locations.

Since the mode of travel was by auto, the interview could be carefully reviewed without interruption. The knowledge engineer could use the recorder for making comments about the interviews while reviewing the interviews and driving between interview locations. However, recording comments would have been easier if two tape recorders had been used; one for playing back the interview and one for recording review comments.

Another successful interview technique was the use of "repair scenarios." The knowledge engineer used data from U.S. Air Force airfield pavement features to construct the four scenarios shown in Appendix D. No expert knew the exact location of the feature, only the geographic region where the feature was located. Since this limitation was not an insurmountable obstacle, planners were able to identify feasible rehabilitation alternatives.

Repair scenarios also helped identify the most knowledgeable engineers. Engineers with the most experience were able to quickly identify key pieces of data and then suggest two or three feasible solutions. For example, Mr Borgwald, a retired MAJCOM pavements engineer with more than 26 years of airfield experience, was able to identify feasible solutions for each of the four scenarios in Appendix D in as little as 30 seconds while taking no more than three minutes. Less experienced engineers could also identify feasible solutions, but often used more data to arrive at their conclusions. Therefore, it took them longer to solve each of the scenarios.

TRAVEL ITINERARY

DATES	ACTION	DESTINATION
4 Oct 89	Travel	Dayton, Ohio
5 Oct 89	Interview	HQ AFLC/DEMM WPAFB, Ohio 45433
6 Oct 89	Interview	WRDC/FIBE WPAFB, Ohio 45433
7 Oct 89	Travel	Norfolk, Virginia
8-9 Oct 89	Weekend/Holiday	
10 Oct 89	Interview	HQ TAC/DEMM Langley AFB, Virginia
11 Oct 89	Travel	Charleston AFB
12 Oct 89	Travel	Panama City, Florida
13 Oct 89	Interview	HQ AFESC/DEMP Tyndall AFB, Florida
14 Oct 89	Travel	Vicksburg, Mississippi
15 Oct 89	Weekend	
16 Oct 89	Interview	US Army Corps of Engineers Waterways Experiment Station Vicksburg, MS 39180
17 Oct 89	Travel	Scott AFB, IL
18 Oct 89	Interview	HQ MAC/DEMM Scott AFB, IL
19 Oct 89	Travel	Omaha, Nebraska
20 Oct 89	Interview	HQ SAC/DEMM Offutt AFB, Nebraska
	Interview	US Army Corps of Engineers CEMRD-ED-4 Omaha, Nebraska
21 Oct 89	Travel	Chicago, Illinois
22 Oct 89	Weekend	
23 Oct 89	Interview	American Concrete Pavement Ass Arlington Heights, IL 60004
23 Oct 89	Travel	Champaign, Illinois

DOMAIN EXPERT INFORMATION SHEET

NAME: Mr. Carl Borgwald **TITLE OR POSITION**: Retired Air Force Logistics Command (AFLC) MAJCOM Pavement Engineer

PHONE: **MAIL ADDRESS:**

YEARS IN CURRENT ASSIGNMENT:

EXPERIENCE: Briefly describe previous pavement related positions you have held. Please include the number of years you worked in each of those positions.

1963 - 1989: Headquarters AFLC MAJCOM pavement engineer

1947 - 1963: Worked for an Oklahoma consultant as a highway pavement engineer with other civil engineering duties.

PLEASE RATE YOUR EXPERIENCE IN EACH OF THE FOLLOWING AREAS:

3 = Very Experienced 2 = Moderately Experienced

1 = Little Experience 0 = No Experience

AIRFIELD MAINTENANCE AND REPAIR <u>PLANNING:</u>

Portland Cement Concrete: 3 Asphalt Concrete: 3

AIRFIELD MAINTENANCE AND REPAIR <u>DESIGN:</u>

Portland Cement Concrete: 2 Asphalt Concrete: 2

AIRFIELD MAINTENANCE AND REPAIR <u>CONSTRUCTION:</u>

Portland Cement Concrete: 3 Asphalt Concrete: 3

COMMENTS:

DOMAIN EXPERT INFORMATION SHEET

NAME: Mr. Cliff Sander

TITLE OR POSITION: Tactical Air Command (TAC) Pavement Engineer

PHONE:

MAIL ADDRESS: HQ TAC/DEMM
Langley AFB, VA

YEARS IN CURRENT ASSIGNMENT: 7

EXPERIENCE: Briefly describe previous pavement related positions you have held. Please include the number of years you worked in each of those positions.

1983 - 1989: Headquarters TAC pavement engineer

1978 - 1983: Headquarters TAC assistant pavement engineer

1974 - 1978: Base civil engineer at Langley AFB

1970 - 1974: U.S. Army construction battalion engineering officer

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PLEASE RATE YOUR EXPERIENCE IN EACH OF THE FOLLOWING AREAS:

3 = Very Experienced 2 = Moderately Experienced

1 = Little Experience 0 = No Experience

AIRFIELD MAINTENANCE AND REPAIR <u>PLANNING:</u>

Portland Cement Concrete: 3 Asphalt Concrete: 3

AIRFIELD MAINTENANCE AND REPAIR <u>DESIGN:</u>

Portland Cement Concrete: 2 Asphalt Concrete: 2

AIRFIELD MAINTENANCE AND REPAIR <u>CONSTRUCTION:</u>

Portland Cement Concrete: 3 Asphalt Concrete: 3

COMMENTS:

DOMAIN EXPERT INFORMATION SHEET

NAME: Maj Edward Miller

TITLE OR POSITION: Chief of Airfield Operations Division

PHONE:

MAIL ADDRESS: HQ AFESC/DEMM
Tyndall AFB, FL 32403

YEARS IN CURRENT ASSIGNMENT: 2

EXPERIENCE: Briefly describe previous pavement related positions you have held. Please include the number of years you worked in each of those positions.

1988 - 1990: Chief of Airfield Operations Division at the U.S. Air Force Engineering and Services Center, Panama City, Fl.

1985 - 1988: Chief of Operations and Maintenance

1983 - 1985: Chief of Civil Section and Assistant Professor of Civil Engineering for the Air Force Institute of Technology at Dayton, Ohio

1981 - 1983: Research engineer at the Air Force Weapons Laboratory, New Mexico

1977 - 1981: Division engineer for Pacific region

1974 - 1977: Chief of Planning and Program Development Sections at Osan AB, Korea

1972 - 1974: Design Engineer and Chief of Program Development

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PLEASE RATE YOUR EXPERIENCE IN EACH OF THE FOLLOWING AREAS:

3 = Very Experienced 2 = Moderately Experienced

1 = Little Experience 0 = No Experience

AIRFIELD MAINTENANCE AND REPAIR PLANNING:

Portland Cement Concrete: 3 Asphalt Concrete: 3

AIRFIELD MAINTENANCE AND REPAIR DESIGN:

Portland Cement Concrete: 3 Asphalt Concrete: 3

AIRFIELD MAINTENANCE AND REPAIR CONSTRUCTION:

Portland Cement Concrete: 3 Asphalt Concrete: 3

DOMAIN EXPERT INFORMATION SHEET

NAME:	Mr. Raymond Rollings	**TITLE OR POSITION:**	Research Civil Engineer
PHONE:		**MAIL ADDRESS:**	USAE Waterways Experiment Station ATT: CEWES-GP, P.O. Box 631 Vicksburg, MS 39181-0631

YEARS IN CURRENT ASSIGNMENT: 4

EXPERIENCE: Briefly describe previous pavement related positions you have held. Please include the number of years you worked in each of those positions.

1989 - 1990: Chief, Materials Research and Construction Technology Branch, Pavement Systems Division, Geotech Lab at the USAE Waterways Experiment Station

1983 - 1989: Research Civil Engineer at the USAE Waterways Experiment Station

1981 - 1983: Soils engineer for the 412th Engineering Command at Vicksburg, MS

1979 - 1981: Chief of Construction for the MS Air National Guard at Gulfport, MS

1975 - 1979: Research geotechnical engineer at the U.S. Air Force Engineering and Services Center, Panama City, Fl.

1974 - 1975: Research and Development project officer at the Air Force Weapons Laboratory at Kirtland AFB, NM.

PLEASE RATE YOUR EXPERIENCE IN EACH OF THE FOLLOWING AREAS:

3 = Very Experienced 2 = Moderately Experienced

1 = Little Experience 0 = No Experience

AIRFIELD MAINTENANCE AND REPAIR PLANNING:

Portland Cement Concrete: 1 Asphalt Concrete: 1

AIRFIELD MAINTENANCE AND REPAIR DESIGN:

Portland Cement Concrete: 3 Asphalt Concrete: 2

AIRFIELD MAINTENANCE AND REPAIR CONSTRUCTION:

Portland Cement Concrete: 3 Asphalt Concrete: 2

DOMAIN EXPERT INFORMATION SHEET

NAME: Mr. Terry Sherman **TITLE OR POSITION:** U.S Army Corps of Engineers, Pavement Engineer, Missouri Division, NE

PHONE: **MAIL ADDRESS:**

YEARS IN CURRENT ASSIGNMENT: 2

EXPERIENCE: Briefly describe previous pavement related positions you have held. Please include the number of years you worked in each of those positions.

1988 - 1990: Pavement engineer for the COE Missouri Division Office in Omaha, NE

1982 - 1988: Headquarters Strategic Air Command (SAC) pavement engineer at Offutt AFB, NE

1980 - 1982: COE Materials & Concrete Division (MRD) Laboratory engineer

1976 - 1980: COE pavement engineer for the Alaskan District

1975 - 1976: Wisconsin Department of Transportation engineer

PLEASE RATE YOUR EXPERIENCE IN EACH OF THE FOLLOWING AREAS:

3 = Very Experienced 2 = Moderately Experienced

1 = Little Experience 0 = No Experience

AIRFIELD MAINTENANCE AND REPAIR PLANNING:

Portland Cement Concrete: 3 Asphalt Concrete: 3

AIRFIELD MAINTENANCE AND REPAIR DESIGN:

Portland Cement Concrete: 2 Asphalt Concrete: 2

AIRFIELD MAINTENANCE AND REPAIR CONSTRUCTION:

Portland Cement Concrete: 3 Asphalt Concrete: 3

COMMENTS:

DOMAIN EXPERT INFORMATION SHEET

NAME: Mr. James LaFrenz | **TITLE OR POSITION:** Strategic Air Command Pavement Engineer

PHONE: | **MAIL ADDRESS:** HQ SAC/DEM Offutt AFB, NE

YEARS IN CURRENT ASSIGNMENT: 2

EXPERIENCE: Briefly describe previous pavement related positions you have held. Please include the number of years you worked in each of those positions.

1988 - 1990: Headquarters Strategic Air Command (SAC) pavement engineer at Offutt AFB, NE

1977 - 1988: Consultant engineer for LaFrenz & Associates

1974 - 1976: Pavement evaluation team chief at the U.S. Air Force Engineering and Services Center, Panama City, FL

PLEASE RATE YOUR EXPERIENCE IN EACH OF THE FOLLOWING AREAS:

3 = Very Experienced 2 = Moderately Experienced

1 = Little Experience 0 = No Experience

AIRFIELD MAINTENANCE AND REPAIR PLANNING:

Portland Cement Concrete: 2 Asphalt Concrete: 2

AIRFIELD MAINTENANCE AND REPAIR DESIGN:

Portland Cement Concrete: 2 Asphalt Concrete: 2

AIRFIELD MAINTENANCE AND REPAIR CONSTRUCTION:

Portland Cement Concrete: 3 Asphalt Concrete: 3

COMMENTS:

DOMAIN EXPERT INFORMATION SHEET

NAME: Mr. William Yrjanson

TITLE OR POSITION: American Concrete Pavement Association (ACPA) Engineer

PHONE:

MAIL ADDRESS:

YEARS IN CURRENT ASSIGNMENT: 20

EXPERIENCE: Briefly describe previous pavement related positions you have held. Please include the number of years you worked in each of those positions.

1970 - 1990:	American Concrete Pavement Association Engineer at Arlington Heights, IL
1957 - 1970:	Portland Cement Association highway and airport pavement engineer in Minnesota, North Dakota and South Dakota
1955 - 1957:	U.S. Army COE airport pavement engineer
1950 - 1955:	U.S. Army COE civil engineer involved with dam construction

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PLEASE RATE YOUR EXPERIENCE IN EACH OF THE FOLLOWING AREAS:

3 = Very Experienced   2 = Moderately Experienced

1 = Little Experience   0 = No Experience

AIRFIELD MAINTENANCE AND REPAIR PLANNING:

Portland Cement Concrete: 3   Asphalt Concrete: 2

AIRFIELD MAINTENANCE AND REPAIR DESIGN:

Portland Cement Concrete: 3   Asphalt Concrete: 2

AIRFIELD MAINTENANCE AND REPAIR CONSTRUCTION:

Portland Cement Concrete: 3   Asphalt Concrete: 2

COMMENTS:

DOMAIN EXPERT INFORMATION SHEET

NAME: Mr. John Riechers **TITLE OR POSITION:** Aerospace Engineer

PHONE: **MAIL ADDRESS:** WRDC/FIBE
Wright-Patterson AFB, OH
45433-6553

YEARS IN CURRENT ASSIGNMENT:

EXPERIENCE: Briefly describe previous pavement related positions you have held. Please include the number of years you worked in each of those positions.

1976 - 1990: Aerospace Systems Division research engineer studying aircraft flight, ground, and thermal loads

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PLEASE RATE YOUR EXPERIENCE IN EACH OF THE FOLLOWING AREAS:

3 = Very Experienced 2 = Moderately Experienced

1 = Little Experience 0 = No Experience

AIRFIELD MAINTENANCE AND REPAIR PLANNING:

Portland Cement Concrete: NA Asphalt Concrete: NA

AIRFIELD MAINTENANCE AND REPAIR DESIGN:

Portland Cement Concrete: NA Asphalt Concrete: NA

AIRFIELD MAINTENANCE AND REPAIR CONSTRUCTION:

Portland Cement Concrete: NA Asphalt Concrete: NA

COMMENTS:

APPENDIX D

INTERVIEW PAVEMENT CASE STUDIES

INTERVIEW SCENARIO 1 (A1B)

CLIMATIC REGION: IIIA **LENGTH (ft):** 330 **WIDTH (ft):** 200

CONSTRUCTION DATE: 1956 **PCC THICKNESS (in):** 15 **Mr (psi):** 550

BASE TYPE (USCS): GW-GM **BASE THICKNESS:** 6

BASE MODULUS (k - Top Base): 180

JOINT LENGTH (ft): 25 **JOINT WIDTH (ft):** 25

LONG JOINT TYPE: 6 **TRANS JOINT TYPE:** 2

SUBGRADE (USCS): ML **DEPTH TO WATER TABLE (ft):** 330

AIRCRAFT TRAFFIC (1972-1982): 5% T-33 95% - F-111

TOTAL AVG ANNUAL PASSES: 2000

AIRCRAFT TRAFFIC (1966-1972) 5% T-33 86% - F-4

9% C-9 & L-188

PCI VALUE (NOV 1978): 36

BLOW UP:

CORNER BREAKS:

L/T/D CRACKS: L24.4 M9.5

"D" CRACKING: L10.4 M3.5

JOINT SEAL:

SMALL PATCH: L14.3 M9.5

LARGE PATCH: L1.2

POPOUTS:

PUMPING:

SCALING/MC/CRAZING: L46.4

SETTLEMENT:

SHAT SLAB: L38.1 M2.4

SHRINKAGE CRACKS: L8.8

SPALLING T/L: L0.7 M0.2

SPALLING CORNER:

INTERVIEW SCENARIO 2 (R1A)

CLIMATIC REGION: IA **LENGTH (ft):** 1000 **WIDTH (ft):** 300

CONSTRUCTION DATE: 1955 **PCC THICKNESS (in):** 20 **Mr (psi):** 650

BASE TYPE (USCS): GW-GM **BASE THICKNESS:** 48

BASE MODULUS (k - Top Base): 470

JOINT LENGTH (ft): 25 **JOINT WIDTH (ft):** 25

LONG JOINT TYPE: 6 **TRANS JOINT TYPE:** 1

SUBGRADE (USCS): CL **DEPTH TO WATER TABLE (ft):** 7

AIRCRAFT TRAFFIC (1970-1979): 15% - T33 32% T38 & F106

15% - C130 & L188 1% - C141 25% - KC135 12% B52

AVERAGE ANNUAL PASSES: 4557

AIRCRAFT TRAFFIC (1962-1970): 17% - T33 42% T38 & F106

13% - C130 & L188 13% - KC135 14% B52

AVERAGE ANNUAL PASSES: 6190

PCI VALUE (MAY 1979): 32

BLOW UP: **CORNER BREAKS:** L16.7

L/T/D CRACKS: L62 - M8.3 - H1 **"D" CRACKING:** L5.8

JOINT SEAL: M **SMALL PATCH:** L10.8 - H1.7

LARGE PATCH: **POPOUTS:** **PUMPING:**

SCALING/MC/CRAZING: L54 - M4.2 - H1 **SETTLEMENT:** L1

SHAT SLAB: L5.8 - M3.3 - H2.5 **SHRINKAGE CRACKS:** L5

SPALLING T/L: L5 - M1 - H1 **SPALLING CORNER:** L2.5 - M1.7 - H1.7

INTERVIEW SCENARIO 3 (R23A)

CLIMATIC REGION: IC **LENGTH (ft):** 1000 **WIDTH (ft):** 75

CONSTRUCTION DATE: 1956 **PCC THICKNESS (in):** 16 **Mr (psi):625**

BASE TYPE :ASPHALT CONCRETE(1650) **BASE THICKNESS (in):** 4

SUBASE TYPE: Stabilized Cement **SUBBASE THICKNESS (in):** 5

SUBBASE MODULUS (k - Top Subbase):300

JOINT LENGTH (ft): 25 **JOINT WIDTH (ft):** 12.5

LONG JOINT TYPE: 2 **TRANS JOINT TYPE:** 1

SUBGRADE (USCS): SP-SM **DEPTH TO WATER TABLE (ft):** 20

AIRCRAFT TRAFFIC (1969-1979): 100% - T37

AVERAGE ANNUAL TRAFFIC: 17,700

AIRCRAFT TRAFFIC (1959-1969): 64% - F-4 20% - KC135 16% - B52

PCI VALUE (JULY 1979): 53

BLOW UP: **CORNER BREAKS:**

L/T/D CRACKS:L26 - M24 - H7 **"D" CRACKING:**

JOINT SEAL: **SMALL PATCH:**

LARGE PATCH: **POPOUTS:**L7.1 **PUMPING:**

SCALING/MC/CRAZING: **SETTLEMENT:**

SHAT SLAB: **SHRINKAGE CRACKS:**

SPALLING T/L: L4.9 - M0.2 **SPALLING CORNER:** L0.7

INTERVIEW SCENARIO 4 (R2A)

CLIMATIC REGION: IC **LENGTH (ft):** 200 **WIDTH (ft):** 75

CONSTRUCTION DATE: 1958 **PCC THICKNESS (in):** 15 **Mr (psi):**750

BASE TYPE :STABILIZED CEMENT **BASE THICKNESS (in):** 6

BASE MODULUS (k - Top Base): 400

JOINT LENGTH (ft): 25 **JOINT WIDTH (ft):** 25

LONG JOINT TYPE: 5 **TRANS JOINT TYPE:** 1

SUBGRADE (USCS): SP-SM **DEPTH TO WATER TABLE (ft):** 5

AIRCRAFT TRAFFIC (1973-1978): 5% - F101

55% - C130 & B727 & B737 40% - C141

AVERAGE ANNUAL TRAFFIC: 68,000

AIRCRAFT TRAFFIC (1970-1973): 5% - F101

50% - C130 & B727 & B737 10% - C141 35% - C5A

AVERAGE ANNUAL TRAFFIC: 77,500

PCI VALUE (DEC 1978): 56

BLOW UP:

CORNER BREAKS:

L/T/D CRACKS:L4 - M12.5

"D" CRACKING:

JOINT SEAL: L99

SMALL PATCH:L37.5

LARGE PATCH:L12.5

POPOUTS:

PUMPING:

SCALING/MC/CRAZING: L12.5

SETTLEMENT:

SHAT SLAB:

SHRINKAGE CRACKS:

SPALLING T/L:

SPALLING CORNER: L4.2

APPENDIX E

DECISION TREE INFORMATION

DECISION TREE SUMMARY I-1A
CLIMATE AND DRAINAGE STUDY

TREE NODE	PATH DISCRIMINATORS
Moisture Region (N1)	Dry (A1)
	Wet OR Intermediate (A2)
High Ground Water Seepage? (N2)	Yes (A3)
	No (A4)
Water Table Depth (N3)	<= 10 ft (A5)
	> 10 ft AND < 30 ft (A6)
	>= 30 ft (A7)
Silt or Clay Subgrade? (N4)	Yes (A8)
	No (A9)
Base Layer Exists? (N5)	Yes (A10)
	No (A11)
Base Drainage Time (N6)	Marginal OR Unacceptable (A12)
	Acceptable (A13)
Subgrade Natural Drainage Index (N7)	Well OR Somewhat-Excessively OR Excessively Drained (A14)
	Very-Poor OR Poorly OR Imperfectly OR Moderately-Well Drained (A15)
Temperature Region (N8)	Freeze OR Freeze-Thaw (A16)
	No-Freeze (A17)

NOTES: (1) "N_" is the tree node number (i.e. N4 is Node #4)
(2) "A_" is the tree arc number (i.e. A9 is Arc #9)

DECISION TREE I-1A CONCLUSIONS
CLIMATE AND DRAINAGE STUDY

CONCLUSIONS	DECISION PATHS
C1. Airport Has Significant Moisture Sources.	P1. N1-A1-N2-A3 P2. N1-A2 P3. N1-A1-N2-A4-N3-A5 P4. N1-A1-N2-A4-N3-A6-N4-A8
C2. High Potential For Frost Heave or Significant Freeze-Thaw Damage.	P5. Any Path to C1 Plus N8-A16
C3. Temperature Normally Does Not Support Frost Heave Conditions or Significant Freeze-Thaw Action.	P6. Any Path To C1 Plus N8-A17
C4. Airport Has Insignificant Moisture Sources.	P7. N1-A1-N2-A4-N3-A6-N4-A9 P8. N1-A1-N2-A4-N3-A7
C5. Subsurface Drainage Is Acceptable.	P9. Any Path to C1 Plus N5-A10-N6-A13 P10. Any Path To C4 P11. Any Path to C1 Plus N5-A10-N6-A12-N7-A14 P12. Any Path to C1 Plus N5-A11-N7-A14
C6. Subsurface Drainage Is Unacceptable.	P13. Any Path to C1 Plus N5-A11-N7-A15

NOTES: (1) "N_" is a tree node in DTS I-1A
(2) "A_" is a tree arc in DTS I-1A
(3) "C_" is the conclusion number

DECISION TREE SUMMARY I-1B
STUDY MISSION AIRCRAFT AND PAVEMENT RATE OF DETERIORATION

TREE NODE	PATH DISCRIMINATORS
Mission Status (N1)	New (A1)
	Changed Within Last 5 Years (A2)
	No Recent Change (A3)
Short Term ROD (N2-A4/A5) (N3-A6/A7)	High (A4 & A6)
	Low OR Normal (A5 & A7)
Existing JPCP Thickness (N4)	Less Than Typical Thickness (A8)
	Greater Than Typical Thickness (A9)
Slab Cracking Pattern (N5)	Systematic (A10)
	Localized (A11)
Long Term ROD (N6)	Low OR Normal (A12)
	High (A13)

DECISION TREE I-1B CONCLUSIONS
STUDY MISSION AIRCRAFT AND PAVEMENT RATE OF DETERIORATION

CONCLUSIONS	DECISION PATHS
C1. Structural Improvement Is Needed.	P1. N1-A1
C2. Aircraft Traffic May Be Overloading Pavement Structure.	P2. N1-A2-N2-A4 P3. N1-A2-N2-A5-N4-A8-N5-A10 P4. N1-A3-N3-A7-N6-A13 P5. N1-A3-N3-A6
C3. Aircraft Traffic Is Not Overloading Pavement Structure.	P6. N1-A2-N2-A5-N4-A8-N5-A11 P7. N1-A2-N2-A5-N4-A9 P8. N1-A3-N3-A7-N6-A12

DECISION TREE SUMMARY I-1C
FRICTION STUDY

TREE NODE	PATH DISCRIMINATORS
Expected Aircraft Braking Response (N1)	No Hydroplaning Potential OR Transitional Hydroplaning Problems (A1)
	Potential Hydroplaning Problems (A2)
	High Potential For Hydroplaning (A3)
High Speed Surface? (N2-A4/A5) (N3-A6/A7)	Yes (A4 & A6)
	No (A5 & A7)
Grooved Surface? (N4-A8/A9) (N5-A10/A11)	Yes (A8 & A10)
	No (A9 & A11)
Percent Cross Slope (N6)	<= 1/2 (A12)
	> 1/2 (A13)

DECISION TREE I-1C CONCLUSIONS
FRICTION STUDY

CONCLUSIONS	DECISION PATHS
C1. Surface Skid Resistance Is Acceptable.	P1. N1-A1 P2. N1-A2-N2-A5
C2. Surface Skid Resistance Is Unacceptable.	P3. N1-A2-N2-A4
C3. Surface Skid Resistance Is Highly Unacceptable.	P4. N1-A3
C4. Grooving Is Feasible.	P5. N1-A2-N2-A4-N4-A9 P6. N1-A3-N3-A6-N5-A11
C5. Surface Profile Is Unacceptable.	P7. N1-A2-N2-A4-N4-A8-N6-A12
C6. Functional Overlays Are Needed.	Any Path to C2, C3 OR C5

DECISION TREE SUMMARY I-1D
ROUGHNESS STUDY

TREE NODE	PATH DISCRIMINATORS
High Speed Surface? (N1)	Yes (A1)
	No (A2)
Long Wavelength Roughness Evaluation Results (N2)	Unacceptable (A3)
	Acceptable (A4)
Short Wavelength Roughness Evaluation Results (N3)	Unacceptable (A5)
	Acceptable (A6)
Extent of Roughness (N4)	Large Area OR Entire Section (A7)
	Small Local Area(s) (A8)

DECISION TREE I-1D CONCLUSIONS
ROUGHNESS STUDY

CONCLUSIONS	DECISION PATHS
C1. Long Wavelength Surface Roughness Is Acceptable.	P1. N1-A1-N2-A4 P2. N1-A2
C2. Short Wavelength Surface Roughness Is Acceptable.	P3. N3-A6
C3. Surface Profile Is Unacceptable. Functional Overlays Are Needed. OVERALL Grinding Is Feasible.	P4. N1-A1-N2-A3 P5. N3-A5-N4-A7
C4. Surface Profile Is Unacceptable In Areas. Consider Slab Replacement AND Localized Grinding.	P6. N3-A5-N4-A8

DECISION TREE SUMMARY I-1E
FOD POTENTIAL STUDY

TREE NODE	PATH DISCRIMINATORS
High Speed Surface? (N1)	Yes (A1)
	No (A2)
FOD Condition Index (N2)	Excellent OR Very Good (A3)
	Good OR Fair (A4)
	Poor OR Very Poor OR Failed (A5)
Are Aircraft Towed? (N3)	Yes (A6)
	No (A7)
Aircraft Engine FOD Susceptibility (N4)	Low (A8)
	Medium OR High (A9)
Does Shop Maintenance Control FOD? (N5-A10/A11) (N6-A12/A13) (N7-A14/A15)	Yes (A10, A12 & A14)
	No (A11, A13 & A15)
Facility Use (N8)	Primary (A16)
	Secondary (A17)
FOD Condition Index (N9)	Excellent OR Very Good OR Good OR Fair (A18)
	Poor OR Very Poor OR Failed (A19)
FOD Condition Index (N10)	Excellent OR Very Good OR Good (A20)
	Fair OR Poor (A21)
	Very Poor OR Failed (A22)
Aircraft Engine FOD Susceptibility (N11)	Low OR Medium (A23)
	High (A24)

DECISION TREE I-1E CONCLUSIONS
FOD POTENTIAL STUDY

CONCLUSIONS	DECISION PATHS
C1. Level of FOD Generation Is Acceptable.	P1. N1-A1-N2-A3 P2. N1-A1-N2-A4-N4-A8 P3. N1-A1-N2-A4-N4-A9-N5-A10 P4. N1-A2-N3-A6 P5. N1-A2-N3-A7-N8-A17-N9-A18 P6. N1-A2-N3-A7-N8-A17-N9-A19-N6-A12 P7. N1-A2-N3-A7-N8-A16-N10-A20 P8. N1-A2-N3-A7-N8-A16-N10-A21-N11-A23 P9. N1-A2-N3-A7-N8-A16-N10-A21-N11-A24-N7-A14
C2. Level of FOD Generation Is Unacceptable.	P10. N1-A1-N2-A4-N4-A9-N5-A11 P11. N1-A1-N2-A5 P12. N1-A2-N3-A7-N8-A17-N9-A19-N6-A13 P13. N1-A2-N3-A7-N8-A16-N10-A22 P14. N1-A2-N3-A7-N8-A16-N10-A21-N11-A24-N7-A15

DECISION TREE SUMMARY I-2F
ASSESS PAVEMENT STRUCTURAL INTEGRITY

TREE NODE	PATH DISCRIMINATORS
Structural Condition Index (N1)	< 70 (A1)
	>= 70 (A2)
Pavement Facility Type (N2)	Runway (A3)
	Taxiway OR Apron (A4)
Structural Condition Index (N3)	<= 60 (A5)
	> 60 AND <= 70 (A6)
Facility Use (N4-A7/A8) (N5-A9/A10)	Primary (A7 & A9)
	Secondary (A8 & A10)
Medium & High Severity "D" Cracking (N6-A11/A12) (N8-A13/A14)	>= 40% (A11 & A13)
	< 40% (A12 & A14)
Reactive Aggregate (N7)	Yes (A15)
	No (A16)

DECISION TREE I-2F CONCLUSIONS
ASSESS PAVEMENT STRUCTURAL INTEGRITY

CONCLUSIONS	DECISION PATHS
C1. Tolerable Amount of Structural Distresses.	P1. N1-A2 P2. N1-A1-N2-A3-N3-A6-N4-A7 P3. N1-A1-N2-A4-N5-A10
C2. Intolerable Amount of Structural Distresses.	P4. N1-A1-N2-A3-N3-A5 P5. N1-A1-N2-A3-N3-A6-N4-A8 P6. N1-A1-N2-A4-N5-A9
C3. Intolerable "D" Cracking.	P7. N6-A11
C4. Tolerable "D" Cracking.	P8. N6-A12
C5. Intolerable Reactive Aggregate Distresses.	P9. N7-A15
C6. Tolerable Reactive Aggregate Distresses.	P10. N7-A16
C7. Pavement Has No Severe Durability Problems.	C4 AND C6
C8. Structural Improvement Is Needed.	C3 OR C5

DECISION TREE SUMMARY I-4I
SURFACE CRACKS AND FATIGUE COMPARISON

TREE NODE	PATH DISCRIMINATORS
L/T/Diag Cracking AND Shattered Slabs (N1)	<= 5% (A1)
	> 5% AND <= 20% (A2)
	> 20% (A3)
Fatigue Analysis Available? (N2-A4/A5) (N5-A10/A11) (N7-A14/A15)	Yes (A4, A10 & A14)
	No (A5, A11 & A15)
Past Accumulated Miner's Damage (N3)	>= 0 AND <= 0.40 (A6)
	> 0.40 (A7)
Recent Mission Change? (N4)	Yes (A8)
	No (A9)
Past Accumulated Miner's Damage (N6)	> 0.05 AND <= 0.60 (A12)
	<= 0.05 (A13)
Past Accumulated Miner's Damage (N7)	>= 0.30 (A16)
	< 0.30 (A17)

DECISION TREE I-4I CONCLUSIONS
SURFACE CRACKS AND FATIGUE COMPARISON

CONCLUSIONS	DECISION PATHS
C1. Fatigue Damage Is Acceptable. Small Amount of Visual Cracking And No Fatigue Analysis Completed.	P1. N1-A1-N2-A5
C2. Fatigue Damage Is Acceptable. Small Amount of Visual Cracking Agrees With Fatigue Study.	P2. N1-A1-N2-A4-N3-A6
C3. Fatigue Damage Is Acceptable. Small Amount of Visual Cracking Conflicts With Fatigue Study And There Has Been No Recent Mission Change.	P3. N1-A1-N2-A4-N3-A7-N4-A9
C4. Fatigue Damage Is Unacceptable. Significant Amount of Visual Cracking And No Fatigue Analysis Completed. Structural Improvement Is Needed.	P4. N1-A2-N5-A11
C5. Fatigue Damage Is Unacceptable. Significant Amount of Visual Cracking Agrees With Fatigue Study. Structural Improvement Is Needed.	P5. N1-A2-N5-A10-N6-A12
C6. Fatigue Damage Is Unacceptable. Significant Amount of Visual Cracking Conflicts With Fatigue Study. Structural Improvement Is Needed.	P6. N1-A2-N5-A10-N6-A13
C7. Fatigue Damage Is Unacceptable. Very High Amount of Visual Cracking And No Fatigue Analysis Completed. Structural Improvement Is Needed.	P7. N1-A3-N7-A15
C8. Fatigue Damage Is Unacceptable. Very High Amount of Visual Cracking Agrees With Fatigue Study. Structural Improvement Is Needed.	P8. N1-A3-N7-A14-N8-A16
C9. Fatigue Damage Is Unacceptable. Very High Amount of Visual Cracking Conflicts With Fatigue Study. Structural Improvement Is Needed.	P9. N1-A3-N7-A14-N8-A17
C10. Fatigue Damage Is Unacceptable. Small Amount of Visual Cracking Conflicts With Fatigue Study And There Has Been A Recent Mission Change. Structural Improvement Needed.	P10. N1-A1-N2-A4-N3-A7-N4-A8

DECISION TREE SUMMARY I-6J
GEOMETRIC RESTRICTIONS FOR OVERLAYS

TREE NODE	PATH DISCRIMINATORS
Multiple Sections Being Considered? (N1)	Yes (A1)
	No (A2)
Is Entire Pavement Facility Being Overlaid? (N2)	Yes (A3)
	No (A4)
Feature(s) Location (N3)	Full Pavement Facility Width (A5)
	Keel Area OR Pavement Facility Edge (A6)
Are Border Sections Allowed To Be Overlaid? (N4)	Yes (A7)
	No (A8)
Facility Type (N5)	Runway (A9)
	Taxiway (A10)
	Apron (A11)
Group Length OR Section Length (N6)	< 1000 feet (A12)
	>= 1000 feet (A13)
Group Length OR Section Length (N7)	< 500 feet (A14)
	>= 500 feet (A15)
Group Width AND Length, OR Section Width AND Length < 500 feet (N8)	Yes (A16)
	No (A17)

DECISION TREE I-6J CONCLUSIONS
GEOMETRIC RESTRICTIONS FOR OVERLAYS

CONCLUSIONS	DECISION PATHS
C1. Overlay Geometry Is Acceptable.	P1. N1-A1-N2-A3 P2. N1-A2-N3-A5-N5-A9-N6-A13 P3. N1-A2-N3-A5-N5-A10-N7-A15 P4. N1-A2-N3-A5-N5-A11-N8-A16 P5. N1-A1-N2-A4-N3-A5-N5-A9-N6-A13 P6. N1-A1-N2-A4-N3-A5-N5-A10-N7-A15 P7. N1-A1-N2-A4-N3-A5-N5-A11-N8-A16 P8. N1-A2-N3-A6-N4-A7-N5-A9-N6-A13 P9. N1-A2-N3-A6-N4-A7-N5-A10-N7-A15 P10. N1-A2-N3-A6-N4-A7-N5-A11-N8-A16 P11. N1-A1-N2-A4-N3-A6-N4-A7-N5-A9-N6-A13 P12. N1-A1-N2-A4-N3-A6-N4-A7-N5-A10-N7-A15 P13. N1-A1-N2-A4-N3-A6-N4-A7-N5-A11-N8-A16
C2. Overlay Geometry Is Unacceptable. Structural Overlays Are Infeasible. Safety Enhancing Overlays Are Infeasible.	P14. N1-A2-N3-A6-N4-A8 P15. N1-A1-N2-A4-N3-A6-N4-A8 P16. N1-A2-N3-A5-N5-A9-N6-A12 P17. N1-A2-N3-A5-N5-A10-N7-A14 P18. N1-A2-N3-A5-N5-A11-N8-A17 P19. N1-A1-N2-A4-N3-A5-N5-A9-N6-A12 P20. N1-A1-N2-A4-N3-A5-N5-A10-N7-A14 P21. N1-A1-N2-A4-N3-A5-N5-A11-N8-A17 P22. N1-A2-N3-A6-N4-A7-N5-A9-N6-A12 P23. N1-A2-N3-A6-N4-A7-N5-A10-N7-A14 P24. N1-A2-N3-A6-N4-A7-N5-A11-N8-A17 P25. N1-A1-N2-A4-N3-A6-N4-A7-N5-A9-N6-A12 P26. N1-A1-N2-A4-N3-A6-N4-A7-N5-A10-N7-A14 P27. N1-A1-N2-A4-N3-A6-N4-A7-N5-A11-N8-A17

DECISION TREE SUMMARY I-6K
PAVEMENT SYSTEM ASSESSMENT

TREE NODE	PATH DISCRIMINATORS
Is Structural Improvement Needed? (N1)	Yes (A1)
	No (A2)
Is Overlay Geometry Acceptable? (N2-A3/A4) (N7-A14/A15)	Yes (A3 & A14)
	No (A4 & A15)
PCI Value (N3)	>= 60 (A5)
	< 60 (A6)
PCI Value (N4)	<= 40 (A7)
	> 40 AND < 60 (A8)
	>= 60 (A9)
Subsurface Drainage Is Acceptable AND No Systematic Frost Heave Exists And Frost Protection Is Adequate? (N5-A10/A11) (N6-A12/A13)	Yes (A10 & A12)
	No (A11 & A13)
PCI Value (N8-A16/A17) (N9-A18/A19)	<= 40 (A16 & A18)
	> 40 (A17 & A19)
Is Subsurface Drainage Acceptable? (N12)	Yes (A24)
	No (A25)
Keel Section? (N10)	Yes (A20)
	No (A21)
Full-Facility Width Section And Section Width > 100 Feet? (N11)	Yes (A22)
	No (A23)

DECISION TREE I-6K CONCLUSIONS
PAVEMENT SYSTEM ASSESSMENT

CONCLUSIONS	DECISION PATHS
C1. Overlays Are Feasible.	P1. N1-A2-N7-A14-N8-A17 P2. N1-A1-N2-A3-N4-A7-N5-A10 P3. N1-A1-N2-A3-N4-A8 P4. N1-A1-N2-A3-N4-A9
C2. Overlays Are Not Feasible.	P5. N1-A2-N7-A15 P6. N1-A2-N7-A14-N8-A16 P7. N1-A1-N2-A4 P8. N1-A1-N2-A3-N4-A7-N5-A11
C3. Recycling And Standard Reconstruction Are Feasible.	P9. N1-A2-N7-A15-N9-A18 P10. N1-A2-N7-A14-N8-A16 P11. N1-A1-N2-A3-N4-A7 P12. N1-A1-N2-A3-N4-A8-N6-A13 P13. N1-A1-N2-A4-N3-A6
C4. Recycling And Standard Reconstruction Are Not Feasible. Keel Replacement Is Not Feasible.	P14. N1-A2-N7-A15-N9-A19 P15. N1-A2-N7-A14-N8-A17 P16. N1-A1-N2-A3-N4-A8-N6-A12 P17. N1-A1-N2-A3-N4-A9 P18. N1-A1-N2-A4-N3-A5
C5. Keel Replacement Is Feasible.	P19. Any Path to C3 Plus N10-A20 P20. Any Path to C3 Plus N10-A21-N11-A22
C6. Keel Replacement Is Not Feasible.	Any Path to C4 P21. Any Path to C3 Plus N10-A21-N11-A23
C7. Crack And Seat Is Feasible.	P22. Any Path to C3 Plus N12-A24 AND P2, P3, OR P4.
C8. Crack And Seat Is Not Feasible.	Any Path to C4 P23. Any Path to C3 Plus N12-A25 OR P5 OR P7.

DECISION TREE SUMMARY I-8L
SELECT TYPES OF OVERLAYS

TREE NODE	PATH DISCRIMINATORS
Are Overlays Feasible? (N1)	Yes (A1)
	No (A2)
Overlay Categories (N2)	Safety Enhancing (A3)
	Structural (A4)
PCI Rating (N3-A25/A5/A6/A7/A8) (N8-A26/A17/A18/A19/A20)	Excellent OR Very Good (A25 & A26)
	Excellent OR Very Good OR Good (A5 & A17)
	Good (A6 & A18)
	Fair OR Poor (A7 & A19)
	Very Poor OR Failed (A8 & A20)
Number of "D" Cracked Slabs In Section (N4-A9/A10) (N13-A29/A30)	Low Severity >= 15% OR Medium Severity >= 1% OR High Severity >= 1% (A9 & A29)
	Low Severity < 15% AND Medium Severity < 1% AND High Severity < 1% (A10 & A30)
Reactive Aggregate? (N5-A11/A12) (N14-A31/A32)	Yes (A11 & A31)
	No (A12 & A32)
Number of Scaling Slabs In Section (N6-A13/A14) (N15-A33/A34)	Low Severity >= 30% OR Medium Severity >= 1% OR High Severity >= 1% (A13 & A34)
	Low Severity < 30% AND Medium Severity < 1% AND High Severity < 1% (A14 & A33)
Facility Type? (N16)	Runway (A35)
	Apron (A36)
	Taxiway (A37)
Is Skid Resistance Unacceptable? (N10)	Yes (A23)
	No (A24)
Is Level of FOD Generation Unacceptable? (N9)	Yes (A21)
	No (A22)
Is Surface Profile Acceptable? (N7)	Yes (A15)
	No (A16)
Is An Aircraft Arresting System Located In Pavement Section? (N12)	Yes (A38)
	No (A39)
Is Section Within 1000 Feet of Runway Ends? (N11)	Yes (A40)
	No (A41
Feasible Overlay Area of Sections? (N17)	< 1/2 of Total Group Area (A27)
	>= 1/2 of Total Group Area (A28)

DECISION TREE I-8L CONCLUSIONS
SELECT TYPES OF OVERLAYS

CONCLUSIONS	DECISION PATHS
C1. Bonded JPCP Overlay Is Feasible For Structural Improvement.	P1. N1-A1-N2-A4-N3-A5-N4-A10-N5-A11-N6-A14 P2. N1-A1-N2-A4-N3-A5-N4-A10-N5-A12
C2. Bonded JPCP Overlay Is Feasible For Profile Corrections.	P3. N1-A1-N2-A3-N7-A16-N3-A5-N4-A10-N5-A11-N6-A14 P4. N1-A1-N2-A3-N7-A16-N3-A5-N4-A10-N5-A12
C3. Bonded JPCP Overlay Is Feasible For Friction Enhancement.	P5. N1-A1-N2-A3-N7-A15-N10-A23-N8-A17-N13-A30-N14-A32 P6. N1-A1-N2-A3-N7-A15-N10-A23-N8-A17-N13-A30-N14-A31-N15-A33
C4. Bonded JPCP Overlay Is Not Feasible For Structural Improvement.	P7. N1-A2 P8. N1-A1-N2 AND NOT A4 P9. N1-A1-N2-A4-N3-A5-N4-A10-N5-A11-N6-A13 P10. N1-A1-N2-A4-N3-A5-N4-A9 P11. N1-A1-N2-A4-N3-A7 P12. N1-A1-N2-A4-N3-A8
C5. Bonded JPCP Overlay Is Not Feasible For Profile Corrections.	P7. N1-A2 P13. N1-A1-N2 AND NOT A3 P14. N1-A1-N2-A3-N7-A15 P15. N1-A1-N2-A3-N7-A16-N3-A5-N4-A10-N5-A11-N6-A13 P16. N1-A1-N2-A3-N7-A16-N3-A5-N4-A9 P17. N1-A1-N2-A3-N7-A16-N3-A7 P18. N1-A1-N2-A3-N7-A16-N3-A8
C6. Bonded JPCP Overlay Is Not Feasible For Friction Enhancement.	P7. N1-A2 P13. N1-A1-N2 AND NOT A3 P19. N1-A1-N2-A3-N7-A15-N10-A24 P20. N1-A1-N2-A3-N7-A15-N10-A23-N8-A17-N13-A29 P21. N1-A1-N2-A3-N7-A15-N10-A23-N8-A17-N13-A30-N14-A31-N15-A34 P22. N1-A1-N2-A3-N7-A15-N10-A23-N8-A19 P23. N1-A1-N2-A3-N7-A15-N10-A23-N8-A20
C7. Unbonded JPCP Overlay Is Feasible For Structural Improvement.	P24. N1-A1-N2-A4
C8. Unbonded JPCP Overlay Is Feasible For Profile Corrections.	P25. N1-A1-N2-A3-N7-A16
C9. Unbonded JPCP Overlay Is Not Feasible For Structural Improvement.	P26. N1-A1-N2 AND NOT A4
C10. Unbonded JPCP Overlay Is Not Feasible For Profile Corrections.	P27. N1-A1-N2 AND NOT A3 P28. N1-A1-N2-A3-N7-A15

NOTE: A bonded JPCP overlay is never feasible for FOD control.
An unbonded JPCP overlay is never feasible for FOD control or for skid enhancement.

DECISION TREE I-8L CONCLUSIONS (Cont)
SELECT TYPES OF OVERLAYS

CONCLUSIONS	DECISION PATHS
C11. No Asphalt Overlays Allowed On Apron	P29. N16-A36
C12. Asphalt Overlay Not Allowed On Runway	P30. N16-A35-N12-A38 P31. N16-A35-N12-A39-N11-A40
C13. Asphalt Overlay Allowed On Runway	P32. N16-A35-N12-A39-N11-A41
C14. Asphalt Overlays Allowed On Taxiway	P33. N16-A37
C15. Asphalt Overlay Is Feasible For Structural Improvement.	P34. C13 OR C14 PLUS N1-A1-N2-A4-N3-A6 P35. C13 OR C14 PLUS N1-A1-N2-A4-N3-A7
C16. Asphalt Overlay Is Feasible For Profile Corrections.	P36. C13 OR C14 PLUS N1-A1-N2-A3-N7-A16-N3-A6 P37. C13 OR C14 PLUS N1-A1-N2-A3-N7-A16-N3-A7
C17. Porous Friction Course Is Feasible For Friction Enhancement.	P38. C13 OR C14 PLUS N1-A1-N2-A3-N7-A15-N10-A23-N8-A18 P39. C13 OR C14 PLUS N1-A1-N2-A3-N7-A15-N10-A23-N8-A19
C18. Asphalt Overlay Is Feasible For FOD Control.	P40. C13 OR C14 PLUS N1-A1-N2-A3-N7-A15-N9-A21-N8-A19 P41. C13 OR C14 PLUS N1-A1-N2-A3-N7-A15-N9-A21-N8-A20
C19. Asphalt Overlay Is Not Feasible For Structural Improvement.	C11 OR C12 P7. N1-A2 P37. N1-A1-N2 AND NOT A4 P38. N1-A1-N2-A4-N3-A25 P39. N1-A1-N2-A4-N3-A8
C20. Asphalt Overlay Is Not Feasible For Profile Corrections.	C11 OR C12 P7. N1-A2 P40. N1-A1-N2 AND NOT A3 P41. N1-A1-N2-A3-N7-A15 P42. N1-A1-N2-A3-N7-A16-N3-A25 P43. N1-A1-N2-A3-N7-A16-N3-A8
C21. Porous Friction Course Is Not Feasible For Friction Enhancement.	C11 OR C12 P7. N1-A2 P44. N1-A1-N2 AND NOT A3 P45. N1-A1-N2-A3-N7-A15-N10-A23-N8-A26 P46. N1-A1-N2-A3-N7-A15-N10-A23-N8-A20 P47. N1-A1-N2-A3-N7-A15-N10-A24
C22. Asphalt Overlay Is Not Feasible For FOD Control.	C11 OR C12 P7. N1-A2 P48. N1-A1-N2 AND NOT A3 P49. N1-A1-N2-A3-N7-A15-N9-A21-N8-A26 P50. N1-A1-N2-A3-N7-A15-N9-A21-N8-A20 P51. N1-A1-N2-A3-N7-A15-N9-A22

DECISION TREE SUMMARY I-8M
SELECT DRAINAGE OPTIONS

TREE NODE	PATH DISCRIMINATORS
Is Subsurface Drainage Acceptable? (N1)	Yes (A1)
	No (A2)
Is Reconstruction Feasible? (N2-A3/A4) (N8-A15/A16)	Yes (A3 & A15)
	No (A4 & A16)
Do Longitudinal Drains And Filters Exist? (N3-A5/A6) (N4-A7/A8) (N5-A9/A10)	Yes (A5, A7 & A9)
	No (A6, A8 & A10)
Do Transverse Drains And Filters Exist? (N7)	Yes (A13)
	No (A14)
Drainage Pipe Capacity (N6-A11/A12) (N9-A17/A18)	Marginal OR Unacceptable (A11 & A17)
	Satisfactory (A12 & A18)
Does Section Have Catch Basins? (N12)	Yes (A23)
	No (A24)
Does Section Have Shoulder(s)? (N10)	Yes (A19)
	No (A20)
Catch Basin Condition (N13)	Marginal OR Unacceptable (A25)
	Satisfactory (A26)
Is Overlay Feasible? (N14)	Yes (A27)
	No (A28)
Shoulder Condition (N11)	Marginal OR Unacceptable (A21)
	Satisfactory (A22)

DECISION TREE I-8M CONCLUSIONS
SELECT DRAINAGE OPTIONS

CONCLUSIONS	DECISION PATHS
C1. Install Longitudinal Drains And Filters.	P1. N1-A1-N3-A6 P2. N1-A2-N2-A3-N4-A8
C2. Do Not Install Longitudinal Drains And Filters.	P3. N1-A1-N3-A5 P4. N1-A2-N2-A4 P5. N1-A2-N2-A3-N4-A7
C3. Transverse Drains And Filters Can Be Installed.	P6. N8-A15-N7-A14
C4. Transverse Drains And Filters Cannot Be Installed.	P7. N8-A16 P8. N8-A15-N7-A13
C5. Install Permeable Base Course.	P9. N1-A2-N2-A3
C6. Repair Longitudinal Drains And Filters.	P10. N5-A9-N6-A11
C7. Do Not Repair Longitudinal Drains And Filters.	P11. N5-A10 P12. N5-A9-N6-A12
C8. Repair Transverse Drains And Filters.	P13. N8-A15-N7-A13-N9-A17
C9. Do Not Repair Transverse Drains And Filters.	P14. N8-A15-N7-A13-N9-A18
C10. Repair Catch Basins.	P15. N12-A23-N13-A25
C11. Do Not Repair Catch Basins.	P16. N12-A24 P17. N12-A23-N13-A26
C12. Repair Shoulder(s).	P18. N10-A19-N11-A21
C13. Do Not Repair Shoulder(s).	P19. N10-A20 P20. N10-A19-N11-A22

DECISION TREE SUMMARY I-8N
SELECT M&R OPTIONS

TREE NODE	PATH DISCRIMINATORS
Joint Shape Factor (N1)	Marginal OR Unacceptable (A1)
	Satisfactory (A2)
Are Reactive Aggregate Distresses Tolerable? (N2)	Yes (A3)
	No (A4)
Is "D" Cracking Tolerable? (N3)	Yes (A5)
	No (A6)
Percent of Joints That Are Spalled (N4)	> 25% (A7)
	<= 25% (A8)
Section Location (N5)	Facility Edge (A9)
	Keel OR Full Facility Width (A10)
Does Pavement Have Severe Durability Problems? (N6)	Yes (A11)
	No (A12)
Do Load Transfer Distresses Exist? (N7)	Yes (A13)
	No (A14)
Is Load Transfer Efficiency Known? (N8)	Yes (A15)
	No (A16)
Are Structural Improvements Needed? (N9)	Yes (A17)
	No (A18)
Load Transfer Efficiency (N10)	< 70% (A19)
	>= 70% (A20)
Load Transfer Efficiency (N11)	< 50% (A21)
	>= 50% (A22)

DECISION TREE I-8M CONCLUSIONS
SELECT M&R OPTIONS

CONCLUSIONS	DECISION PATHS
C1. Joint Restoration Is Feasible.	P1. N1-A1 P2. N1-A2-N2-A3-N3-A5 P3. N1-A2-N2-A3-N3-A6-N4-A7
C2. Joint Restoration Is Infeasible.	P4. N1-A2-N2-A4 P5. N1-A2-N2-A3-N3-A6-N4-A8
C3. Joint Load Transfer Restoration Is Feasible.	P6. N5-A10-N6-A12-N7-A14-N8-A15-N9-A17-N10-A19 P7. N5-A10-N6-A12-N7-A14-N8-A15-N9-A18-N11-A21 P8. N5-A10-N6-A12-N7-A13
C4. Joint Load Transfer Restoration Is Infeasible.	P9. N5-A9 P10. N5-A10-N6-A11 P11. N5-A10-N6-A12-N7-A14-N8-A16 P12. N5-A10-N6-A12-N7-A14-N8-A15-N9-A17-N10-A20 P13. N5-A10-N6-A12-N7-A14-N8-A15-N9-A18-N11-A22

DECISION TREE II
CONTRACTOR CONCERNS

TREE NODE	PATH DISCRIMINATORS
Alternative Type (N1)	Overlay (A1) Reconstruction (A2) Restoration OR Maintenance (A3)
Is Subsurface Drainage Acceptable? (N3)	Yes (A8) No (A9)
Required Construction Expediency (N6)	Fast Track (A10) Normal (A11)
Local Contractors With Experience (N2-A4/A5) (N4-A14/A15) (N7-A12/A13) (N9-A16/A17)	Yes (A4, A12, A14 & A16) No (A5, A13, A15 & A17)
Job Scope (N5-A6/A7) (N10-A20/A21) (N11-A18/A19)	>= 35,000 S.Y. (A6, A18 & A20) < 35,000 S.Y. (A7, A19 & A21)
Job Scope (N8)	Large (A22) Small (A23)

DECISION TREE II CONCLUSIONS
CONTRACTOR CONCERNS

CONCLUSIONS	DECISION PATHS
C1. Alternative Is Approved For Construction.	P1. N1-A1-N2-A4 P2. N1-A1-N2-A5-N5-A6 P3. N1-A2-N3-A8-N7-A12 P4. N1-A2-N3-A8-N7-A13-N10-A20 P5. N1-A3-N4-A14 P6. N1-A3-N4-A15-N8-A22
C2. Alternative Is Not Approved For Construction.	P7. N1-A1-N2-A5-N5-A7 P8. N1-A2-N3-A9-N6-A10 P9. N1-A2-N3-A9-N6-A11-N9-A17-N11-A19 P10. N1-A2-N3-A8-N7-A13-N10-A21 P11. N1-A3-N4-A15-N8-A23
C3. Alternative Is Reluctantly Approved For Construction.	P12. N1-A2-N3-A9-N6-A11-N9-A16 P13. N1-A2-N3-A9-N6-A11-N9-A17-N11-A18

DECISION TREE SUMMARY III
AIRFIELD MANAGER CONCERNS

TREE NODE	PATH DISCRIMINATORS
Alternative Type (N1)	Overlay OR Reconstruction (A1)
	Drainage (A2)
	Restoration OR Maintenance (A3)
Drainage Work Options (N2)	Repair Catch Basins OR Repair Longitudinal Drains OR Install Longitudinal Drains OR Repair Shoulder (A4)
	Install Base Course OR Install Transverse Drains OR Repair Transverse Drains (A5)
Facility Type (N3)	Runway (A6)
	Taxiway OR Apron (A7)
Allowable Closure Time (N4)	Overnight (A8)
	1 to 10 Days (A9)
	More Than 10 Days (A10)
Fast Track Construction? (N5-A11/A12) (N10-A21/A22)	Yes (A11 & A21)
	No (A12 & A22)
Is Subsurface Drainage Acceptable? (N6)	Yes (A13)
	No (A14)
Proximity of Aircraft To Work Site (N7)	< 100 ft (A15)
	>= 100 ft (A16)
Is Large Amount of Debris Generated During Demolition? (N8)	Yes (A17)
	No (A18)
Alternative Methods With Lengthy Construction Periods (N9)	Reconstruction (A19)
	Other Types of Work (A20)

DECISION TREE III CONCLUSIONS
AIRFIELD MANAGER CONCERNS

CONCLUSIONS	DECISION PATHS
C1. All Options Are Operationally Acceptable.	P1. N1-A3 P2. N1-A2-N2-A4 P3. N1-A1-N3-A7 P4. N1-A2-N2-A5-N3-A7 P5. N1-A1-N3-A6-N4-A10
C2. No Option Is Operationally Acceptable.	P6. N1-A1-N3-A6-N4-A8 P7. N1-A1-N3-A6-N4-A9-N5-A12
C3. Overlay Options Are Operationally Feasible.	P8. N1-A1-N3-A6-N4-A9-N5-A11
C4. Reconstruction, Base Installation And Transverse Drainage Work Are Operationally Acceptable.	P9. N1-A1-N3-A6-N4-A9-N5-A11-N6-A13
C5. Reconstruction, Base Installation And Transverse Drainage Work Are Not Operationally Acceptable.	P10. N1-A1-N3-A6-N4-A9-N5-A11-N6-A14
C6. All Work Is Safe To Construct.	P11. N7-A16 P12. N7-A15-N8-A18
C7. All Work Other Than Reconstruction Is Safe To Construct.	P13. N7-A15-N8-A17-N9-A20
C8. Standard Reconstruction And Recycling Are Not Safe To Construct.	P14. N7-A15-N8-A17-N9-A19-N10-A22
C9. Standard Reconstruction And Recycling Are Safe To Construct.	P15. N7-A15-N8-A17-N9-A19-N10-A21

DECISION TREE SUMMARY IV
JOINT TYPE SELECTION AND DESIGN DLTE DETERMINATION

TREE NODE	PATH DISCRIMINATORS
Is Reconstruction OR An Unbonded Overlay Feasible? (N1)	Yes (A1)
	No (A2)
Is A Bonded JPC OR An Asphalt Structural Overlay Feasible? (N2)	Yes (A3)
	No (A4)
Are FWD Determined DLTE Evaluation Results Available? (N3-A5/A6)	Yes (A5)
	No (A6)
Existing JPCP Joint Types (N4-A7/A8)	All Joint Types Are Doweled (A7)
	Some Joints Rely On Aggregate Interlock OR Keyways For Load Transfer (A8)
User Specified Joint Types (N5-A9/A10)	All Joint Types Are Doweled (A9)
	Some Joints Rely On Aggregate Interlock OR Keyways For Load Transfer (A10)

DECISION TREE IV CONCLUSIONS
JOINT TYPE SELECTION AND DESIGN DLTE DETERMINATION

CONCLUSIONS	DECISION PATHS
C1. All Bonded JPCP And Asphalt Overlay Joints Will Be Dummy Joints.	P1. N1-A2-N2-A3
C2. All Joint Types Are As Specified By User.	P2. N1-A1
C3. Use Lowest DLTE Of All Existing JPCP Joints.	P3. N1-A2-N2-A3-N3-A5
C4. Use DLTE of 85% For All Joints For All Seasons.	P4. N1-A2-N2-A3-N3-A6-N4-A7 P5. N1-A1-N5-A9
C5. Use Foxworthy's Model And Regional Mean Daily Temperatures For Each Season To Determine DLTEs.	P6. N1-A2-N2-A3-N3-A6-N4-A8

DECISION TREE SUMMARY V
MATERIAL PROPERTY SELECTION FOR THICKNESS DESIGN

TREE NODE	PATH DISCRIMINATORS
Is Reconstruction Feasible? (N1)	Yes (A1)
	No (A2)
Type Of Overlay (N2)	Bonded JPCP (A3)
	Asphalt (A4)
	Unbonded JPCP (A5)
Is "Eh^3" Of Unbonded JPCP Overlay Twice As Large As "Eh^3" Of Existing JPCP? (N3)	Yes (A6)
	No (A7)
Is "Eh" Of Unbonded JPCP Overlay Less Than "Eh" Of Existing JPCP? (N4)	Yes (A8)
	No (A9)

DECISION TREE V CONCLUSIONS
MATERIAL PROPERTY SELECTION FOR THICKNESS DESIGN

CONCLUSIONS	DECISION PATHS
C1. Fatigued Single Layer JPCP Thickness Determined Using: (a) Existing JPCP "E" And "Mr" Values. (b) Existing Base Or Subgrade "k" Value. (c) Past Fatigue Damage.	P1. N1-A2-N2-A3 P2. N1-A2-N2-A5-N3-A7-N4-A8
C2. Fatigued Single Layer JPCP Thickness Determined Using: (a) User Specified New Design JPCP "E" And "Mr" Values. (b) Existing Base Or Subgrade "k" Value. (c) Past Fatigue Damage Included.	P3. N1-A2-N2-A5-N3-A7-N4-A9
C3. New Single Layer JPCP Thickness Determined Using: (a) User-Specified New Design JPCP "E" And "Mr" Values. (b) Use Subgrade "k" Value of 200 psi/in. (c) Past Fatigue Damage NOT Included.	P4. N1-A2-N2-A5-N3-A6
C4. New Single Layer JPCP Thickness Determined Using: (a) User-Specified New Design JPCP "E" And "Mr" Values. (b) Existing Base or Subgrade "k" Value. (c) Past Fatigue Damage NOT Included.	P5. N1-A2-N2-A4 P6. N1-A1

DECISION TREE SUMMARY VI
JOINT SPACING RECOMMENDATIONS

TREE NODE	PATH DISCRIMINATORS
Asphalt Overlay? (N1)	Yes (A1)
	No (A2)
For A JPCP Bonded Overlay, Will The Spacing Be Within 10% Of the Allowable Joint Spacing? (N2)	Yes (A3)
	No (A4)
Bonded JPCP Overlay? (N3)	Yes (A5)
	No (A6)
Is Reconstruction Feasible? (N4)	Yes (A7)
	No (A8)
Section Location (N5)	Full Facility Width (A9)
	Edge OR Keel (A10)
Stabilized Base Or Subgrade? (N6-A11/A12) (N7-A13/A14)	Yes (A11 & A13)
	No (A12 & A14)
New Longitudinal Joint Spacing? (N8)	> 20 ft (A15)
	<= 20 ft (A16)

DECISION TREE VI CONCLUSIONS
JOINT SPACING RECOMMENDATIONS

CONCLUSIONS	DECISION PATHS
C1. Use Joint Spacing of 4ℓ.	P1. N1-A2-N2-A4-N3-A6-N4-A8 P2. N1-A2-N2-A4-N3-A6-N4-A7-N5-A9-N6-A11 P3. N1-A2-N2-A4-N3-A6-N4-A7-N5-A10-N7-A13
C2. Use Joint Spacing of 5ℓ.	P4. N1-A2-N2-A4-N3-A6-N4-A7-N5-A9-N6-A12 P5. N1-A2-N2-A4-N3-A6-N4-A7-N5-A10-N7-A14
C3. Saw And Seal Joints To Match Existing Transverse And Longitudinal Joints.	P6. N1-A1
C4. Use Existing Joint Spacing For Longitudinal And Transverse Joints.	P7. N1-A2-N2-A3
C5. Use Longitudinal Construction Joints.	P8. N8-A16
C6. Do Not Use Longitudinal Construction Joints.	P9. N8-A15

APPENDIX F

U.S. AIR FORCE GROUP INDICES FOR AIRCRAFT

AIRCRAFT GROUP INDEX

LIGHT LOAD			MEDIUM LOAD							HEAVY LOAD		
1	2	3	4	5	6	7	8	9	10	11	12	13
C-123	A-7	F-111	C-130	C-7	737	*727	707	C-141	C-5	*KC-10	747	B-52
	A-10	*FB-111		*C-9	*T-43	KC-97	*E-3	*B-1		DC10	*E-4	
	A-37			DC9	C-119		C-135			L1011		
	F-4			C-54	EC-121		*KC-135					
	F-5			C-131			VC-137					
	*F-15			C-140								
	F-16			T-29								
	F-10X											
	T-33											
	T-37											
	T-38											
	T-39											
	T-46											
	OV-10											

* CONTROLLING AIRCRAFT

GROSS WEIGHT LIMITS FOR AIRCRAFT GROUPS

	1	2	3	4	5	6	7	8	9	10	11	12	13
	PAVEMENT CAPACITY IN KIPS												
LOWEST POSSIBLE GROSS WEIGHT	35	5	50	60	20	40	85	105	135	325	230	300	175
HIGHEST POSSIBLE GROSS WEIGHT	60	68	120	175	110	150	175	335	480	770	590	780	490
	PAVEMENT CAPACITY IN KILOGRAMS x 1000												
LOWEST POSSIBLE GROSS WEIGHT	16	2	23	27	9	18	39	48	61	147	104	136	79
HIGHEST POSSIBLE GROSS WEIGHT	27	31	54	79	50	68	79	152	218	349	268	354	222

PASS INTENSITY LEVEL

LEVEL	Groups 1, 2, 3	Groups 4, 5, 6, 7, 8, 9, 10	Groups 11, 12, 13
I	300,000 PASSES	50,000 PASSES	15,000 PASSES
II	50,000 PASSES	15,000 PASSES	3,000 PASSES
III	15,000 PASSES	3,000 PASSES	500 PASSES
IV	3,000 PASSES	500 PASSES	100 PASSES
V	300,000 PASSES	50,000 PASSES	15,000 PASSES
VI	50,000 PASSES	15,000 PASSES	3,000 PASSES

NOTES

IN REFERENCE TO THE ALLOWABLE GROSS LOAD (AGL) TABLE:

- *A* — *Denotes lowest possible empty gross weight of any aircraft within the group exceeds the AGL of the pavement. Pavement cannot support aircraft for respective pass intensity level.*
- *+* — *Denotes no weight restrictions. AGL of the pavement exceeds the greatest possible gross weight of any aircraft in the group.*

Pass intensity levels V and VI are used with reduced subgrade strengths to determine the maximum allowable loads during the frost-melt period.

UNITED STATES AIR FORCE
ENGINEERING & SERVICES CENTER
TYNDALL AIR FORCE BASE, FLORIDA

RELATED DATA

ENGINEER	DATE	DRAWING NUMBER
N/A	MAR 87	APPENDIX G
DRAWN: PATRICK	SCALE: N/A	SHEET 1 OF —

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